

**MAKERERE**



**UNIVERSITY**

**EXPLOITATION OF *Brycinus nurse* (Rüppell, 1832) AND *Engraulicypris bredoi* (Poll, 1945)  
IN LAKE ALBERT, UGANDA: IMPLICATIONS FOR MANAGEMENT**

**BY**

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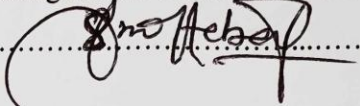
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**A THESIS SUBMITTED TO THE DIRECTORATE OF RESEARCH AND GRADUATE  
TRAINING IN FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF THE  
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**JANUARY 2026**

## DECLARATION

I, **NAKIYENDE HERBERT**, declare that this thesis is my original work and has not been submitted for award of a degree in any other University, and that no part of this thesis is plagiarized. I confirm that all external references and sources have dully been acknowledged. I have read and understood the plagiarism regulations of Makerere University.

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## APPROVAL

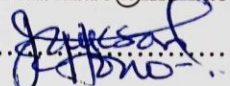
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## **DEDICATION**

I dedicate this work to my beloved parents, Mr. George William Sande Mudima and Mrs. Joyce Namaganda Mudima; my cherished wife, Flavia Nakasiita Nakiyende; and our precious creations: Asupasa Mark Nakiyende, Honest Mathew Mudiima, Samuel Marvin Nakiyende, Michelle Blessing Magoba Nakiyende, and Conrad Elijah Nakiyende. This dedication also extends to my brothers, sisters, friends, and well-wishers.

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## LIST OF ACRONYMS

ACARE	African Centre for Aquatic Research and Education
ACIAR	Australian Center for International Agricultural Research
AGLs	African Great Lakes
ANCOVA	Analysis of Covariance
ANOVA	Analysis of Variance
CAS	Catch Assessment Survey
CPUE	Catch Per Unit Effort
FAO	Food and Agricultural Organization
FL	Fork Length
FS	Frame Survey
GDP	Gross Domestic Product
IDRC	International Development Research Center.
IUU	Illegal Unreported and Unregulated
KMFRI	Kenya Marine and Fisheries Research Institute
LVFO	Lake Victoria Fisheries Organization
MSY	Maximum Sustainable Yield
NaFIRRI	National Fisheries Resources Research Institute
NARO	National Agricultural Research Organization
NEMA	National Environmental Management Authority
SDG	Sustainable Development Goals
SL	Standard Length
SPS	Small Pelagic Species
TL	Total Length
UBOS	Uganda Bureau of Statistics
UN	United Nations
USD	United States Dollar
WHO	World Health Organization

## ABSTRACT

Lake Albert supports a diverse artisanal fishery characterized by multi-species exploitation using a wide range of fishing gears. The fishery is increasingly dominated by two small pelagic fish species (SPS), *Brycinus nurse* and *Engraulicypris bredoi*, which are primarily harvested using vertically stacked small seine nets operated in conjunction with artificial light attraction. Despite their growing importance, the ecosystem-level impacts of these fishing techniques on both target and non-target fish stocks remain poorly understood. The use of these light assisted gears has also generated conflicts with fishers targeting large-bodied species, particularly Nile perch (*Lates niloticus*), due to perceptions that these gears negatively affect the recruitment and availability of larger species stocks.

This study was conducted on the Uganda portion of Lake Albert between September 2019 and July 2022, with the aim of evaluating the socio-ecological effects of light-attraction fishing techniques as a basis for informing sustainable fisheries management. A mixed-method approach was adopted, integrating literature reviews, experimental fishing, catch assessment surveys, hydroacoustic assessments, and stakeholder consultations. These methods were used to quantify catch rates, species abundance and distribution, life-history traits, exploitation patterns, and biological reference points relevant to the management of the lake's artisanal fisheries.

Results indicated a substantial light-attraction fishing effort on Lake Albert, accounting for approximately 40% of the lake's active fishing vessels. Fishing activity peaked during moonless nights and was significantly ( $P < 0.05$ ) associated with higher SPS catch rates. High bycatch, unregulated expansion of light-fishing effort, excessive net stacking, and the increasing use of solar-powered fishing lights emerged as the principal drivers of user conflict within the fishery.

Marked spatial variation in SPS abundance was observed across the lake. *Engraulicypris bredoi* dominated catches in the central region ( $F(2, 15240) = 172.45, p < 0.001$ ), whereas *B. nurse* was more abundant in the southern region ( $F(2, 4447) = 41.166, p < 0.001$ ). Hydroacoustic survey and artisanal catch statistics consistently demonstrated the dominance of SPS, which constituted approximately 82% and 70% of total biological scatter and catch volume, respectively, indicating a high standing biomass of small pelagic species stocks in Lake Albert.

Analysis of life history traits revealed pronounced sexual dimorphism in length at 50% maturity ( $L_{m50}$ ) for both species. Male *E. bredoi* matured at a larger size (31.6 mm) than females (23.9

mm), whereas female *B. nurse* matured earlier and at a larger size (60.9 mm) than males (56.8 mm). Both species exhibited positive allometric growth and high condition factor: *B. nurse* ( $b = 3.21$ ,  $K = 2.08$ ) and *E. bredoi* ( $b = 3.06$ ,  $K = 1.27$ ), suggesting favourable physiological condition and relatively healthy stock status.

Experimental fishing trials demonstrated that light attraction significantly enhanced SPS catch rates ( $p < 0.05$ ), with near-zero catches recorded under control treatments without light. This finding corroborates observed fishing patterns characterized by intensified effort during dark nights and confirms the functional necessity of artificial light in SPS exploitation. Bycatch, particularly of *Lates niloticus*, *Oreochromis niloticus*, *Hydrocynus forskahlii*, and *Distichodus niloticus*, was predominantly recorded in shallow inshore waters ( $< 20$  m depth). These habitats serve as critical zones for biodiversity conservation, recruitment, and stock replenishment, underscoring the need for their protection from intensive fishing pressure.

Net stacking was found to significantly increase both SPS catch rates and bycatch. Optimal SPS yields with comparatively minimal bycatch were achieved at a net depth of approximately 16 meters (eight panels), suggesting a potential management threshold for regulating fishing effort. Estimates of maximum sustainable yield (MSY) and fishing effort at MSY indicated that current exploitation levels for both *E. bredoi* (~90,000 t; 2500 boats) and *B. nurse* (~37,000 t; 2000 boats) remained below 2022 observed thresholds, implying that SPS were not yet fully exploited.

These findings have important implications for sustainable management of Lake Albert's SPS fisheries. The study recommends revising existing fishing regulations to incorporate SPS-specific management measures, including species-specific licensing, protection of inshore breeding and nursery habitats, regulation of net stacking, and promotion of standardized solar fishing lights. In addition, strengthening regional collaboration for comprehensive stock assessments and harmonized fisheries management frameworks is essential. These measures, when implemented could contribute to reduction in bycatch, mitigate fishing conflicts, and promote the long-term coexistence of multi-species fisheries within the Lake Albert ecosystem.

## CHAPTER ONE: INTRODUCTION

### 1.1. Background to the study

Inland fisheries play a vital role in global food security and socio-economic development by providing food, income, and employment to millions of people worldwide (FAO, 2022). Globally, fish contributes approximately 17% of the total animal protein intake and supports direct employment to about 62 million people in the primary production sector (FAO, 2022). Inland fisheries are particularly important in developing countries, where they underpin rural livelihoods and serve as an affordable source of high-quality animal protein (Welcomme et al., 2010; Hara et al., 2021).

Historically, capture fisheries were the dominant source of global fish production. However, over the past three decades, capture fisheries output has stagnated and declined, contributing only 49% of total global fish supply by 2022, slightly lower than aquaculture production (FAO, 2022). In Africa's Great Lakes (AGLs), including Lakes Albert, Victoria, Kivu, Malawi, and Tanganyika, the contribution of large-bodied fish species to total landings has markedly declined (Cowx and Ogutu-Owhayo, 2019; Kolding et al., 2019; LVFO, 2022; FAO, 2024). This decline has been driven by multiple interacting factors, including increasing anthropogenic pressures, rapid population growth, overexploitation, illegal, unreported and unregulated (IUU) fishing, habitat degradation, and climate change. Compounding these challenges is a persistent scarcity of robust, long-term fisheries data, which has constrained the development and implementation of science-based management strategies for these complex multispecies fisheries.

In Uganda, the predominantly freshwater, capture-based fisheries sector is a key component of the national economy, contributing approximately 3% to the national Gross Domestic Product (GDP) and up to 12% to the Agricultural GDP (UBOS, 2022). The sector sustains the livelihoods of more than three million people along the value chain, encompassing fishing, post-harvest handling, processing, value addition, transportation, marketing and associated support services. Nile perch (*Lates niloticus*) remains the national the country's primary fish export commodity (UBOS, 2022; Mpomwenda et al., 2022).

Large-bodied fish species (> 20 cm, total length-TL) historically dominated Uganda's major lake fisheries, including Lakes Victoria, Albert, Kyoga, George, and Edward. These species included *L. niloticus* (Nile perch), *Oreochromis niloticus* (Nile tilapia), *Bagrus docmak*, *Clarias gariepinus*, *Bagrus bajad*, *Hydrocynus forskahlii*, *Alestes baremose*, and *Protopterus aethiopicus* (Holden, 1963, Cadwalladr & Stoneman, 1966; Greenwood, 1966; Matsuishi *et al.*, 2006; and Mbabazi *et al.*, 2012). However, sustained fishing pressure and inadequate management have resulted in marked declines in their abundance and overall contribution to commercial and artisanal catches (von Sarnowski, 2004; Mbabazi *et al.*, 2012; Nakiyende *et al.*, 2013; Kolding *et al.*, 2019; FAO, 2020; NaFIRRI, 2021; Mpomwenda *et al.*, 2022; Nakiyende *et al.*, 2023).

The decline in large-bodied fish species has far-reaching socio-economic and nutritional consequences, including reduced availability of high-quality animal protein, loss of income and employment, and constraints on achieving the recommended per capita fish consumption of 25 kg per year (FAO, 2020). Consequently, Uganda's per capita fish consumption, estimated at 12.5 kg (Obiero *et al.*, 2019), remains substantially below this benchmark. Furthermore, shortages of large-bodied fish species raw materials have also contributed to the closure or underutilization of several fish processing facilities (Namisi, 2000). Ultimately, the shifts in fish production and species composition have significant implications for achieving the United Nations Sustainable Development Goals (SDGs), particularly on poverty reduction (SDG1), zero hunger and food insecurity (SDG2), and life below water and sustainable fisheries (SDG14) (Colglazier, 2015; Arora & Mishra, 2019; Halisçelik & Soytas, 2019).

Against this broader backdrop of declining large-bodied fish species and their profound socio-economic, nutritional, and developmental implications, Lake Albert represents a particularly instructive case within Uganda's inland fisheries landscape. The lake's fisheries have undergone substantial structural and compositional changes over time, yet these shifts have largely occurred in the absence of sustained, systematic scientific assessment and adaptive management. Consequently, Lake Albert's fisheries have remained vulnerable to both ecological degradation and socio-economic shocks, reinforcing national trends of declining per capita fish consumption and underutilization of fisheries infrastructure. This historical research and management gap underscores the need for robust, ecosystem-based stock assessment approaches to inform sustainable fisheries management on Lake Albert, particularly in the context of increasing

exploitation pressure, environmental change, and the imperative to contribute meaningfully to national development goals and the Sustainable Development Agenda.

### **1.1.1 Historical context of fisheries development and management challenges in Lake Albert**

For much of its history, Lake Albert has remained comparatively neglected in terms of systematic fisheries research and adaptive management, especially when contrasted with other African Great Lakes such as Victoria and Tanganyika. Early fisheries investigations on Lake Albert were sporadic and largely descriptive, with most post-independence studies remaining ad hoc and primarily focused on quantifying fishing effort, gear types, and catch composition (Worthington, 1929; Holden, 1963; Cadwalladr & Stoneman, 1966; Wandera & Balirwa, 2010; Mbabazi et al., 2012). While such studies provide important baseline information, effort and catch statistics alone represent only partial components of comprehensive stock assessment and are insufficient for evidence-based management of a complex multispecies fishery. Consequently, critical aspects such as stock size, exploitation rates, spatial dynamics, biological reference points, and ecosystem interactions have historically received limited attention on Lake Albert.

Commercial exploitation of Lake Albert's fisheries dates back to the early 20th century, when Greek entrepreneurs were among the first to engage in organized fishing operations, largely operating from the Democratic Republic of Congo (DRC) side of the lake and supplying regional markets (Worthington, 1929; Holden, 1963). On the Ugandan side, attempts at industrial-scale processing emerged much later. In 2006, a Nile perch processing facility, the World Catch fish factory, was established at Butiaba with the primary objective of tapping into what was then perceived as abundant Nile perch stocks. However, the factory's operation was short-lived, closing in 2010 due to inadequate and unreliable raw material supply, itself a consequence of declining Nile perch stocks and weak fisheries management systems (Mbabazi et al., 2012; NaFIRRI, 2012). The failure of this investment underscores the risks associated with exploiting Lake Albert's fisheries in the absence of robust scientific assessments and adaptive management frameworks. Moreover, this historical trajectory highlights a persistent gap between exploitation and knowledge generation on Lake Albert and underscores the urgent need for comprehensive, ecosystem-based studies.

### 1.1.2 Development of small pelagic species (SPS) artisanal fishery on African Great Lakes.

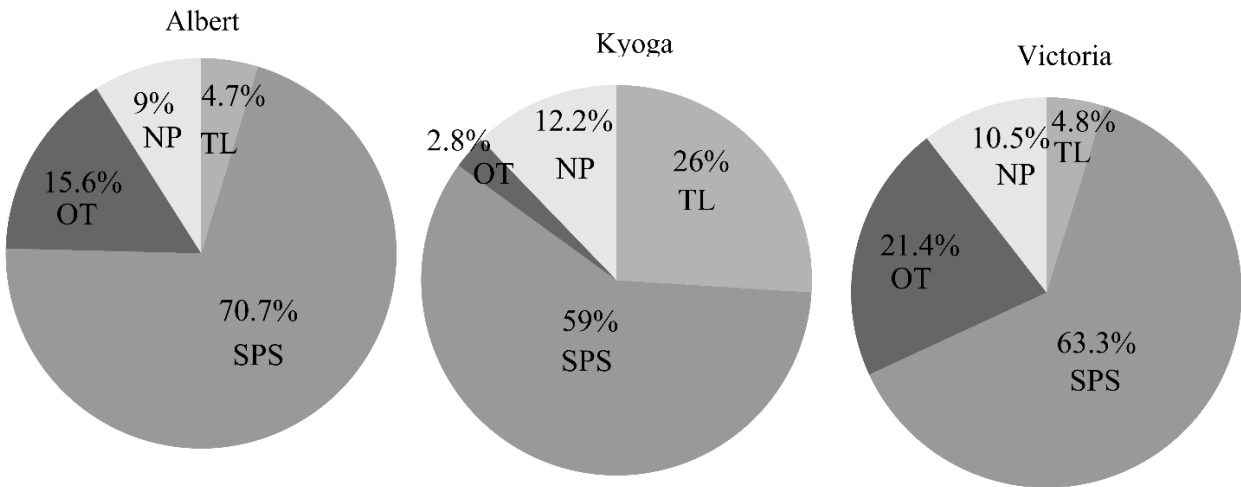
Small pelagic species (SPS) are generally defined as small-bodied, short-lived, schooling fish that occupy the pelagic zone of lakes and seas and are typically harvested using light-assisted or fine-mesh fishing gears (Beverton, 1990; Patterson, 1992). Owing to their high reproductive rates, rapid population turnover, and strong sensitivity to environmental variability, SPS often respond quickly to changes in fishing pressure and ecosystem conditions, making them ecologically significant and economically important components of inland and marine fisheries (Saraux et al., 2019).

Across the Africa's Great Lakes (AGLs), including Lakes Albert, Victoria, Kivu, Malawi, and Tanganyika (Plisnier et al., 2023), there has been a notable shift in fish abundance and catch composition over recent decades, characterized by a declining contribution of large-bodied fish species and a corresponding dominance of SPS in both abundance and catch landings (Mbabazi et al., 2012; Kolding et al., 2019; LVFO, 2021; Nakiyende et al., 2022). This transition reflects fundamental changes in ecosystem structure and fisheries exploitation patterns within the AGLs. In Lakes Tanganyika and Kivu, two clupeid SPS, *Stolothrissa tanganyicae* and *Limnothrissa miodon*, collectively contribute approximately 50% of total annual fish catches, underscoring their importance in regional food security and fisheries productivity (Kolding et al., 2019).

Similarly, within Uganda, SPS constitute the bulk of fish landings from Lakes Victoria, Albert, and Kyoga (**Figure 1.1-1**) (LVFO, 2021; 2022; Kolding et al., 2019; Mbabazi et al., 2019; Nakiyende et al., 2023). The small-sized silver cyprinid, *Rastrineobola argentea* (locally known as mukene-Uganda, dagaa-Tanzania, and omena-Kenya), accounts for about 60% of annual total landings estimated at about 588,000 tonnes (t) and 53,000 t in Lakes Victoria and Kyoga respectively (LVFO, 2021; NaFIRRI, 2015; 2024). In Lake Albert, two dominant SPS *Engraulicypris bredoi* (locally known as muziri) and *Brycinus nurse* (ragoogi) collectively contribute 70% of the approximately 348,000 t annual total catch (**Figure 1.1-1**) (NaFIRRI, 2021; NELSAP, 2021; Nakiyende et al., 2023). These species have therefore become central to the ecological functioning of these lakes and the livelihoods of dependent fishing communities.

Globally, several interacting factors have been attributed to drive such shifts in fish community composition and abundance, including intensive exploitation of large-bodied predators

leading to altered predator-prey dynamics, environmental degradation, habitat modification, and increasing climate variability and change. However, despite the growing dominance of SPS in the AGLs, the relative importance and mechanistic pathways of these drivers remain poorly understood at regional and lake-specific scales. In particular, limited empirical evidence exists to disentangle the ecological and socio-economic processes underpinning the rise of SPS-dominated fisheries in the African Great Lakes, highlighting a critical knowledge gap for effective ecosystem-based fisheries management.



**Figure 1.1-1.** Composition of annual total catch landings on Lakes Albert, Kyoga, and Victoria. NP = Nile perch, TL = Tilapia, OT = Other species grouped, SPS = small pelagic species (Source: NaFIRRI, 2015; NELSAP, 2019; NaFIRRI, 2021).

### 1.1.3 Evolution of light-based small pelagic species fishery in Lake Albert.

Lake Albert supports a highly diverse artisanal fishery that targets multiple fish species across a wide range of size classes (Wandera and Balirwa, 2010; Mbabazi et al., 2012; 2019; Nakiyende et al., 2013). This diversity spans from small-sized species such as *E. bredoi*, which rarely exceed 70 mm total length (TL) at maturity, to large-bodied species such as *L. niloticus*, which can attain lengths of up to 2 m TL. The co-existence of such contrasting life-history strategies necessitates the use of multiple fishing gears and harvesting methods, thereby posing substantial regulatory and enforcement challenges for sustainable fisheries management.

Despite the multispecies nature of the Lake Albert fishery, existing management frameworks permit only a limited set of fishing gears, including multifilament gillnets (minimum

mesh size of four inches or > 100 mm), small seine nets (mesh size eight millimeters), and hooks (size nine and below) (Fish (Fishing) Rules, 2010). These regulations were largely designed around large-bodied target species and have struggled to keep pace with the rapid evolution of fishing practices targeting small pelagic species.

Prior to the 1980s, the Lake Albert artisanal fishery was predominantly oriented towards large-bodied species such as *L. niloticus*, *D. niloticus*, *Labeobarbus bynnii*, *Citharinus spp*, *Bagrus bajad*, *O. niloticus*, *H. forskahlii*, and *A. baremose* (Worthington, 1929; Holden, 1963; Cadwalladr & Stoneman, 1966; Greenwood, 1966; and Mbabazi *et al.*, 2012). Harvesting of these species employed a wide range of conventional fishing gears such as gillnets, hooks, beach seines, basket traps, boat seines, boat seines, cast nets, and monofilament gillnets (Worthington, 1929; Holden, 1963; Cadwalladr & Stoneman, 1966; Greenwood, 1966; and Mbabazi *et al.*, 2012). During this period, fishing activities were spatially and temporally structured, and conflicts among fishers were relatively limited. Overexploitation of these stocks, however, resulted in marked declines in abundance and catch contribution, creating ecological and economic space for the emergence of alternative fisheries. By the early 2000s, a distinct fishery targeting two dominant SPS; *E. bredoi* and *B. nurse*, had become established in Lake Albert (Mbabazi *et al.*, 2012; Kolding *et al.*, 2019; Mbabazi *et al.*, 2019; NaFIRRI, 2021).

In its early stages, the SPS fishery operated largely at a subsistence level. Harvesting was predominantly undertaken by women and children, who collected fish during daylight hours by wading through shallow inshore habitats and scooping them using perforated basins (NaFIRRI, 2021). This practice later evolved into the use of mosquito nets in the same shallow inshore zones, increasing efficiency but also raising concerns regarding juvenile bycatch and habitat disturbance (Nakiyende *et al.*, 2023). As participation in the fishery expanded to include adult men, harvesting techniques became increasingly commercialized and technologically advanced. Fishers adopted small seine nets formed by joining two to four panels, operated in combination with two to three kerosene lights during moonless nights to attract fish (NaFIRRI, 2012; Mbabazi *et al.*, 2012; Nakiyende *et al.*, 2023). Over time, continued intensification of the fishery led to further technological adaptations, including the use of larger, vertically stacked seine nets comprising multiple joined panels (up to 20 stacked panels) and the replacement of kerosene lamps with solar-powered lights (Mbabazi *et al.*, 2012; Nakiyende *et al.*, 2023). These developments substantially

increased fishing efficiency and spatial reach, but also intensified fishing pressure on SPS stocks and raised new ecological, social, and management concerns.

#### **1.1.4 Fishing conflicts and opportunities in Lake Albert, Uganda.**

The rapid expansion of SPS fisheries and the widespread adoption of light-attraction techniques, notably solar-powered lighting, on Lake Albert have fueled divergent stakeholder divergence and intensified fishing conflicts (NaFIRRI, 2012, Nakiyende et al., 2023). On Lake Albert, the fishery is increasingly characterized by tensions between fishers using light-assisted methods and those targeting large-bodied species such as *L. niloticus*, *A. baremose*, *H. forskahlii*, and *B. bajad*. While these large-bodied species are traditionally harvested with large-mesh gears, they are frequently captured as juvenile bycatch in the fine-mesh nets used for light-attraction fishing. The simultaneous operation of these distinct practices within shared grounds, especially during night-time hours, has heightened spatial competition and increased the frequency of user-group conflicts.

Stakeholders opposing light fishing, notably those involved in the large-bodied species fishery, argue that light attraction techniques accelerate the decline of large fish stocks. These concerns are largely attributed to perceived high levels of bycatch rates, particularly the incidental capture and mortality of juvenile large-bodied species within SPS catches. Other concerns include excessive fishing effort, competition for limited fishing space, and the high intensity of solar-powered lights, which are believed to increase the visibility of stationary fishing gears such as gillnets and hooks, thereby facilitating fish avoidance and reducing catch efficiency for traditional gears (NaFIRRI, 2012). In contrast, proponents of light fishing contend that light attraction is indispensable for effective exploitation of SPS and maintain that their fishing activities do not significantly contribute to the decline of large species. They argue that observed reductions in large species stock are primarily driven by prolonged overfishing, climate variability and change, pollution, habitat degradation, and the widespread use of undersized and illegal gears within large-bodied species fishery.

Given the consistent trend of SPS dominance across several AGLs, including Lake Albert, these fisheries present a strategic pathway for development and livelihood enhancement. Empirical data from Lake Albert underscores this potential: SPS fishing accounts for approximately 70% of

total annual catch volumes, effectively buffering the impact of declining landings from large-bodied species (Mbabazi et al., 2012; NELSAP, 2019; NaFIRRI, 2021). This shift supports a broad socio-economic network, engaging 40% of active fishing vessels and supporting the livelihoods of nearly 60% of the lakeshore population. The sector exhibits a distinct demographic structure, with male youths dominating harvesting operations while women primarily drive the post-harvest and processing value chains (Efitre et al., 2023).

Moreover, the transition from high-value, large-bodied fish to high-volume, low-value SPS has complex economic implications. While SPS contributes roughly 40% of beach-level revenue, the reliance on sheer volume to sustain household incomes necessitates careful management. If managed within biologically sustainable limits, a strategic reallocation of effort toward SPS could alleviate fishing pressure on overexploited stocks like *L. niloticus*, facilitating their recovery. Consequently, the SPS fishery serves as both a vital nutritional safety net and a primary economic engine, provided that management frameworks can balance increased harvesting intensity with long-term ecosystem stability.

Realizing these opportunities requires sound scientific understanding and effective management interventions. However, at the height of fishing conflicts, no comprehensive empirical study had quantified the extent of large-species bycatch associated with light fishing or evaluated its broader ecosystem-level impacts in Lake Albert. The divergence in stakeholder perspectives surrounding light fishing therefore highlights a critical knowledge gap. Hence, robust empirical evidence is thus needed to assess the ecological and socio-economic consequences of light attraction fisheries and to provide an objective basis for policy formulation, conflict resolution, and sustainable management of multispecies fisheries in Lake Albert.

## **1.2. Problem Statement.**

Small pelagic species, notably *Engraulicypris bredoi* and *Brycinus nurse*, have become the dominant contributors to fish production in Lake Albert, playing an increasingly important role in food security, livelihoods, and the resilience of the lake's multispecies fishery. However, the rapid expansion of this light-based fishery has occurred in the absence of adequate empirical information required for evidence-based management. In particular, the ecological and socio-economic implications of artificial light attraction, the primary harvesting technique for SPS, remain poorly

understood, despite growing resistance from fishers targeting large-bodied species, especially Nile perch.

Key concerns relate to the indiscriminate nature of light-assisted fishing, including elevated bycatch of juveniles of large-bodied species, increased pressure on inshore breeding and nursery habitats, and potential alteration of fish community structure and ecosystem functioning. The persistent conflicts between fishers targeting SPS using light-assisted gears and those targeting large-bodied species using conventional gears, undermines social cohesion, regulatory compliance, and effective fisheries governance on Lake Albert.

Management responses to these challenges are further constrained by critical knowledge gaps on SPS stock size, spatial and temporal distribution, exploitation patterns, population structure, life-history traits, and biological reference points. In addition, ecosystem-level impacts of light fishing, particularly on non-target species and habitat use, have not been quantitatively assessed. Without this information, fisheries managers lack the scientific basis to design SPS-specific regulations, manage overlapping fishing regimes, and prevent overcapitalization of the rapidly expanding SPS fishery.

If unaddressed, the Lake Albert SPS fishery risks following a trajectory similar to that of formerly dominant large-bodied species such as *Citharinus citharus*, which declined sharply under unsustainable exploitation. Such a collapse would have far-reaching consequences for food and nutrition security, livelihoods, and the long-term sustainability of Lake Albert's fisheries. This study therefore evaluates the socio-ecological impacts of artificial light-assisted fishing in SPS-dominated fisheries to generate empirical evidence needed to inform adaptive, ecosystem-based fisheries management and reduce conflicts among resource users.

### **1.3. Study Objectives.**

#### **1.3.1 General Objective.**

The overall objective of this study was to examine the exploitation patterns and ecological impacts of light-based harvesting technologies on the populations of *Engraulicypris bredoi* and *Brycinus nurse* and bycatch species in Lake Albert and provide knowledge for evidence-based management of their stocks.

### 1.3.2 Specific Objectives.

The specific objectives of the study were to:

1. Evaluate stakeholder perceptions of artificial light fishing technologies targeting small pelagic species in Lake Albert.

**Hypothesis:** H<sub>01</sub> (Null): There are no significant differences in perceptions and attitudes towards artificial light-assisted fishing among fisheries stakeholder groups, and these perceptions do not influence compliance levels, conflict occurrence, or fisheries management decisions.

2. Map the spatial and temporal distribution of the two small pelagic species (*Engraulicypris bredoi* and *Brycinus nurse*) and light fishing effort in Lake Albert.

**Hypothesis:** H<sub>02</sub> (Null): The spatial and temporal distributions of *E. bredoi* and *B. nurse* do not vary significantly across habitats or lunar phases in Lake Albert.

3. Determine the life history traits of *Engraulicypris bredoi* and *Brycinus nurse* in Lake Albert.

**Hypothesis:** H<sub>03</sub> (Null): Life-history traits of *E. bredoi* and *B. nurse* do not differ significantly across habitats in Lake Albert.

4. Quantify the effects of artificial light configurations (light type and luminous intensity) and gear specifications (net-panel depth and mesh size) on the catch rates (CPUE), size structure, and recruitment patterns of target species (*Engraulicypris bredoi* and *Brycinus nurse*) and non-target species in Lake Albert.

**Hypothesis:** H<sub>04</sub> (Null): Variation in net-panel depth and mesh size, luminous intensity (lumens), and light source (solar vs. kerosene) does not significantly influence the mean length-at-capture, species-specific biomass (CPUE), or the catch-to-bycatch ratios of *Engraulicypris bredoi* and *Brycinus nurse*.

5. Establish biological reference points of *Engraulicypris bredoi* and *Brycinus nurse* in Lake Albert.

**Hypotheses:** H<sub>05</sub> (Null): Current exploitation levels of *E. bredoi* and *B. nurse* do not differ significantly from estimated biological reference points for sustainable harvest.

### 1.4. Research questions.

The study was guided by the following five key research questions:

1. What perceptions and attitudes do different fisheries stakeholders around Lake Albert hold towards artificial light-assisted fishing, and how do these perceptions influence compliance, conflict dynamics, and fisheries management decision-making?
2. How do the spatial and temporal distributions of *Engraulicypris bredoi* and *Brycinus nurse* vary across habitats and lunar cycles in Lake Albert?
3. How do the life history traits (e.g., growth patterns, size at maturity, condition factor) of *Engraulicypris bredoi* and *Brycinus nurse* vary across habitats in Lake Albert, and what implications do these variations have for sustainable management?
4. How do net-panel configuration and light type and intensity influence catch rates and selectivity of target SPS (*Engraulicypris bredoi* and *Brycinus nurse*) and non-target species across habitats in Lake Albert?
5. What levels of biological reference points (e.g., maximum sustainable yield, optimal fishing effort) would promote sustainable harvest of *Engraulicypris bredoi* and *Brycinus nurse* in Lake Albert?

### **1.5. Justification of the study.**

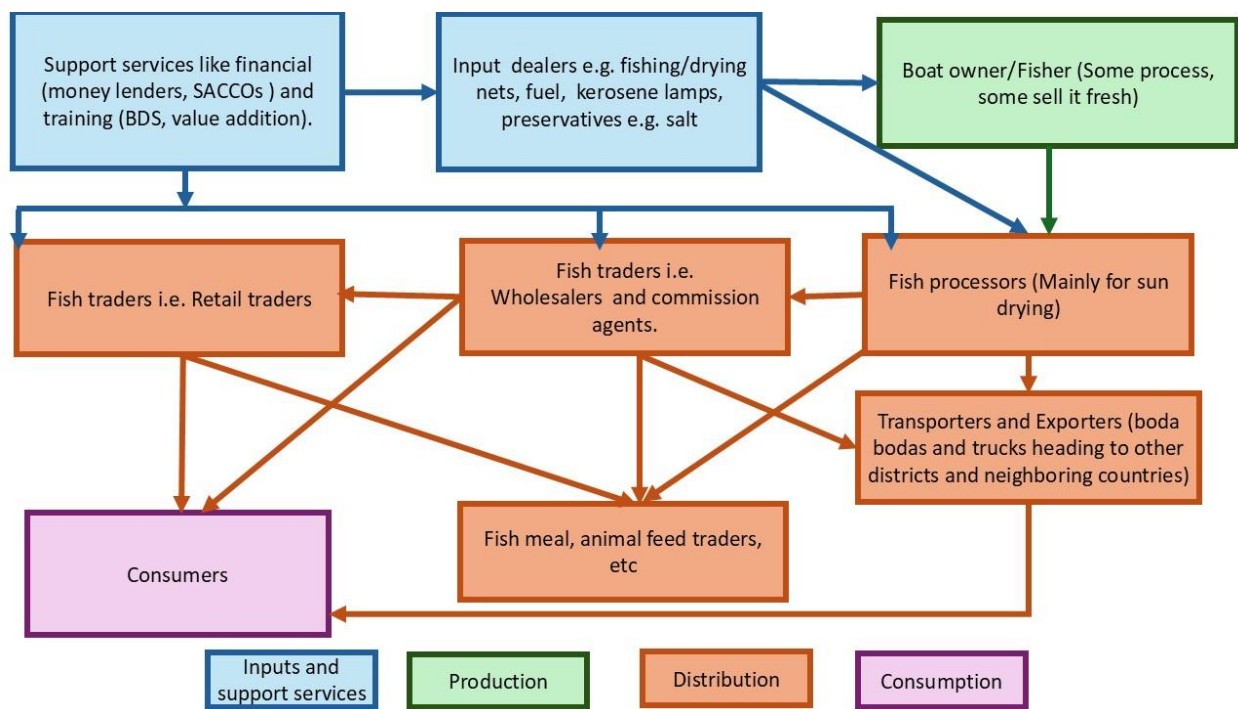
The rapid emergency and increasing dominance of the small pelagic species fishery in Lake Albert, particularly *Engraulicypris bredoi* and *Brycinus nurse*, represents both an adaptive response to the collapse of large-bodied fish species stocks and a critical opportunity to realign fisheries development with principles of sustainability and ecosystem-based management. While the shift toward SPS exploitation has helped to sustain livelihoods and fish supply in the short term, its continued expansion in the absence of sound scientific guidance risks repeating the overexploitation trajectory previously experienced by large-bodied species. A comprehensive understanding of the ecological dynamics, exploitation patterns, and management requirements of the SPS fishery is therefore essential to ensure the long-term resilience of Lake Albert's multispecies fisheries.

Therefore, this study responds to an urgent need for empirical, science-based evidence to support sustainable management of *E. bredoi* and *B. nurse* fisheries, particularly in the context of rapidly evolving fishing technologies such as artificial light attraction and net stacking. By assessing stock abundance, distribution, life-history traits, and exploitation levels across short- and medium-term temporal scales, the study provides critical information necessary for predicting

catch potential and future stock trends. Such evidence is fundamental for establishing biological reference points, informing adaptive regulations, and guiding effective fisheries governance.

The findings contribute directly to the formulation of SPS-specific management strategies, including regulation of fishing effort, spatial zoning, and control of light-assisted fishing practices. Moreover, by quantifying bycatch and habitat-related impacts, the study supports efforts to mitigate fishing conflicts, protect critical breeding and nursery habitats, and maintain ecosystem integrity.

The findings of this research are of relevance to a broader spectrum of stakeholders across the SPS fisheries value chain (**Figure 1.5-1**), including fishers, processors, traders, fisheries managers, policymakers, investors, local governments, researchers, and academic institutions. Beyond Lake Albert, the study provides insights applicable to other African Great Lakes including Lakes Victoria and Kivu and inland waters such Kyoga and Nabugabo experiencing similar shifts towards SPS-dominated fisheries, and where similar fishing technologies and management challenges are increasingly evident. The comparative relevance of these findings strengthens their utility beyond Lake Albert, supporting regional learning and harmonized fisheries management approaches across shared water bodies.



**Figure 1.5-1.** Value chain map for the small fish species, including *Rastrineobola argentea* (Mukene), *Engraulicypris bredoi* (Muziri) and *Brycinus nurse* (Ragoge). Source: Modified from AfDB report, 2022.

Overall, this research contributes to evidence-based policy reform, informed investment planning, and sustainable fisheries development, while supporting food and nutrition security, livelihoods, and the long-term productivity of Lake Albert’s aquatic ecosystems. In addition to evidence-based decision-making, the study further contributes to the realization of several United Nations Sustainable Development Goals (SDGs), notably SDG 1 (No Poverty) through livelihood security, SDG 2 (Zero Hunger) by improving access to affordable and nutritious fish, and SDG 14 (Life Below Water) through the promotion of sustainable exploitation and conservation of aquatic resources (Table 1.5-1) (Hák & Moldan, 2016; Allen et al., 2018; Cowx & Ogutu-Owhayo, 2019). By integrating ecological sustainability with socio-economic benefits, this research provides a robust foundation for long-term fisheries resilience in Lake Albert and comparable inland fisheries systems.

**Table 1.5-1.** Contribution of the current study to Sustainable Development Goals (SDGs).

SDG	Sustainable Development Goal	Contribution of Policy Brief
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SDG 1	No Poverty	The study supports poverty reduction by promoting sustainable fishing practices, which are essential for the livelihoods of fishing communities, helping to alleviate poverty.
SDG 2	Zero hunger	By promoting sustainable fisheries management, the study contributes to ensuring the availability of fish as a vital source of nutrition, helping to achieve zero hunger.
SDG 5	Gender equality	The study recognizes the role of women and youths in fisheries and suggests affirmative actions, such as promotion of user-friendly production and processing technologies like solar energy, contributing to gender equality.
SDG 8	Decent work and economic growth	Sustainable fisheries support economic growth and provide decent work opportunities, particularly for fishing communities, aligning with the goal of decent work and economic growth.
SDG 12	Responsible consumption and production	The study advocates for responsible fishing practices, which align with the goal of responsible consumption and production of fish resources.
SDG 13	Climate action	Encouraging the use of environmentally friendly solar lights over kerosene lanterns reduces carbon emissions, contributing to climate action.
SDG 14	Life below water	The study promotes sustainable fisheries management, reducing overfishing and bycatch, which aligns with the goal of conserving life below water.
SDG 15	Life on Land	Sustainable fisheries management helps protect terrestrial and aquatic ecosystems, supporting the goal of conserving life on land.
SDG 17	Partnerships for the goals	The study encourages collaborative research, involving governments, agencies, research institutions, departments, and fishing communities, promoting partnerships for achieving the SDGs.

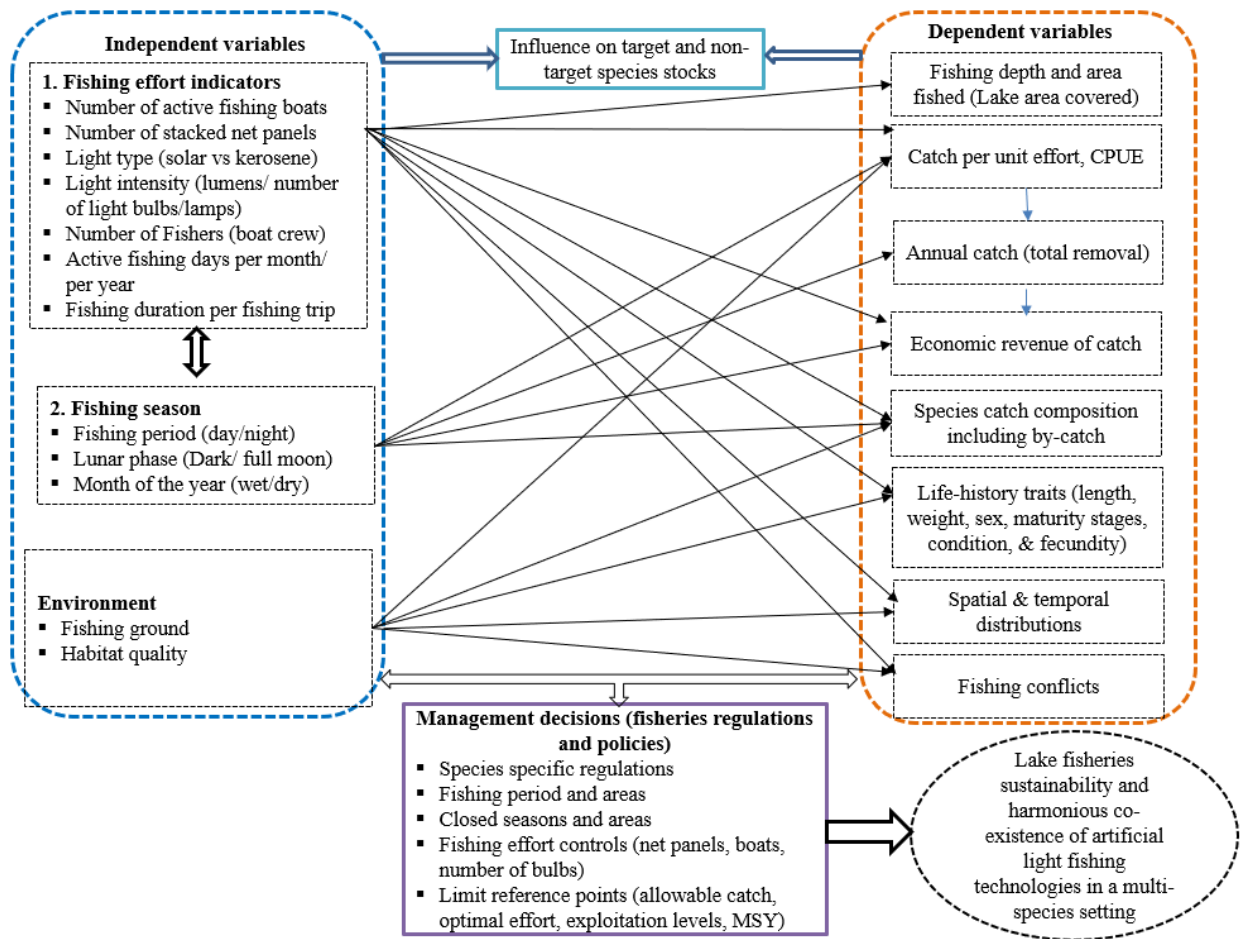
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## 1.6. Conceptual Framework.

This study is anchored in an integrated socio-ecological systems conceptual framework, which recognizes fisheries as complex adaptive systems composed of resource users (fishers and institutions), biological resources (fish populations), and the supporting habitats and ecosystems within which these interactions occur (**Figure 1.6-1**). The framework draws on complementary theories from fisheries ecology, evolutionary biology, ecosystem science, economics, and governance to comprehensively examine exploitation dynamics of *Engraulicypris bredo* and *Brycinus nurse* in the Lake Albert Small Pelagic Species (SPS) fishery.

By drawing on these theories, the study examines how key independent variables, namely; light fishing effort inputs (such as light type, intensity, and net stacking), temporal factors (seasonality and lunar phase), and habitat characteristics (inshore shallow versus offshore deep areas), influence critical dependent outcomes. These include fishing depth, catch rates (both for target and bycatch species), size structure of fish populations, and spatial distribution patterns (**Figure 1.6-1**). Integrating these empirical variables within a strong theoretical context enables a deeper exploration of the ecological processes, gear interactions, and socio-technical dynamics that shape the sustainability of the SPS fishery in Lake Albert.

At the core of the study is the Common-Pool Resource (CPR) Theory (Ostrom, 1990; Schlager, 2004), which conceptualizes fisheries as shared resources that are rivalrous and non-excludable, thus prone to overexploitation in the absence of effective governance. This theory underscores the importance of management institutions and co-management strategies in regulating access and ensuring long-term sustainability. Closely related is the Tragedy of the Commons (Hardin, 1968), which explains the tendency of open-access resources such as fisheries to be overexploited in the absence of well-defined user rights and effective governance. In such settings, individual fishers are incentivized to maximize personal gain, often at the cost of long-term resource sustainability. This concept is particularly relevant to Lake Albert, where increasing fishing pressure, driven by light fishing and net stacking, threatens the ecological integrity of small pelagic fish stocks. The theory underscores the urgent need for robust governance mechanisms, including community-inclusive approaches, to ensure equitable and sustainable resource use.



**Figure 1.6-1.** Conceptual framework illustrating relationships between independent (left) and dependent (right) variables of the study.

To understand the ecological vulnerability of *E. bredoi* and *B. nurse*, the study draws from Life History Theory (Stearns, 1992), which examines how species allocate energy toward growth, reproduction, and survival. SPS typically exhibit rapid growth, early maturation, and high fecundity traits that make them resilient but also vulnerable to recruitment overfishing, especially during juvenile stages when light fishing gears may increase catchability. This justifies the need for biological reference points, temporal closures, and size-based regulations to preserve reproductive capacity. The framework also employs the Precautionary Principle (FAO, 1995), advocating for proactive management interventions even in the face of scientific uncertainty. Given the emerging and poorly regulated nature of light fishing gears on Lake Albert, precautionary measures such as gears limitation, and fishing closures are vital to mitigate risks to fish stocks and ecosystems. From a socio-institutional lens, the study is informed by Cross-Scale

Governance Theory (Cash et al., 2006), which recognizes the need for coordination across local, national, and regional governance levels. The transboundary nature of Lake Albert fisheries necessitates joint monitoring and enforcement mechanisms between Uganda and the Democratic Republic of Congo to address cross-border fishing, gear migration, and shared conservation objectives.

Furthermore, aligned with this study is the principle of Maximum Sustainable Yield (MSY), a classical fisheries concept introduced by Graham (1935) and later formalized through biological reference points (Schaefer, 1954). MSY serves as a benchmark for the maximum level of harvest that allows fish populations to replenish, thus avoiding recruitment overfishing. In this study, MSY and associated reference points such as fishing mortality and biomass thresholds are applied to assess whether current exploitation levels of *B. nurse* and *E. bredoi* are biologically sustainable and to inform potential harvest control rules. Bioeconomic models further enhance this analysis by integrating ecological and economic dimensions of fisheries. These models, as articulated by Clark (1990; 2010), evaluate the interplay between stock dynamics and fisher behaviour under various policy and effort scenarios. In resource-dependent contexts like Lake Albert, bioeconomic models provide valuable insights into the trade-offs between maximizing short-term economic returns and ensuring long-term ecological viability, enabling the design of balanced and effective management interventions.

To capture the broader ecological context, the study also draws on Ecosystem-Based Fisheries Management (EBFM) principles (Pikitch et al., 2004; Browman & Stergiou, 2004), advocating for a holistic management approach that transcends single-species focus to consider multispecies interactions, habitat integrity, and environmental variability. In this regard, the study examined spatial and temporal abundance and distribution of both target and non-target species (bycatch) trends, and the ecological impacts of light fishing technologies on the lake ecosystem. This perspective is critical in recognizing the interconnectedness of species and habitats within Lake Albert and the cascading effects of exploitation on ecosystem resilience.

The human dimensions of fisheries management are equally integral to this framework. Fishers are not just resource users but adaptive agents whose perceptions, decision-making, and compliance influence management outcomes (Sen and Nielsen, 1996; Jentoft, 2000; Pomeroy & Rivera-Guieb, 2006; Béné et al., 2007). The study captures local knowledge, attitudes toward light fishing, and behavioural responses to seasonal and regulatory changes. It also explores socio-

economic drivers of conflict and cooperation, providing an in-depth understanding of the social fabric underpinning exploitation dynamics and potential pathways for participatory governance. In line with this, the study considers co-management and adaptive management frameworks as practical governance models for complex and dynamic fisheries. Co-management promotes shared responsibility between government agencies and local communities, while adaptive management emphasizes iterative, learning-based responses to ecological and socio-economic feedback (Holling, 1978; Berkes et al., 2001). These approaches are particularly relevant to Lake Albert, where uncertainty, environmental change, and diverse stakeholder interests demand flexible and inclusive solutions.

Technological advances in the fishery are addressed through the lens of fishing technology and gear efficiency. While innovations such as light fishing and net stacking can improve catch rates, they may also increase pressure on juvenile stocks and non-target species if not regulated appropriately (Sainsbury et al., 2000). The study critically assesses the influence of net stacking, light source and intensity, and effort concentration on catch composition and stock structure, informing recommendations on technical controls, such as gear limits and spatial closures. Lastly, the study invokes evolutionary ideas like Survival of the Fittest and the “Fit Gene” theory (Darwin, 1859), using them a benchmark to describe how selective pressures from fishing gear and environmental stressors may shape species composition and community structure. These dynamics have implications for biodiversity conservation and ecosystem stability, as certain species or life stages may be disproportionately impacted, leading to shifts in trophic relationships and ecosystem functioning.

To address institutional complexity, the framework incorporates governance and institutional theories, including cross-scale governance (Cash et al., 2006) and polycentric governance concepts. Lake Albert’s transboundary nature necessitates coordination between local communities, national agencies, and bilateral mechanisms between Uganda and the Democratic Republic of Congo. These theories provide a basis for recommending harmonized regulations, joint monitoring, and shared enforcement strategies. In addition, the framework recognizes the eight core fisheries management principles, including sustainability, precaution, ecosystem integrity, participation, equity, efficiency, compliance, and adaptability—and links each to practical management functions such as effort control, gear regulation, spatial protection, monitoring, and stakeholder engagement.

Finally, the framework is underpinned by the Precautionary Principle (FAO, 1995) and adaptive management theory (Holling, 1978). Given uncertainties surrounding stock dynamics, environmental variability, and emerging fishing technologies, the study advocates for proactive, learning-based management that iteratively adjusts regulations in response to ecological and socio-economic feedback.

Collectively, these theoretical and conceptual underpinnings provide a robust analytical lens for assessing exploitation patterns, ecological risks, and governance responses in the Lake Albert SPS fishery. They facilitate a holistic understanding of the ecological, technological, and socio-economic factors that shape the sustainability of the fishery and support the development of responsive, precautionary, spatially aware, socially inclusive, institutionally coordinated, and ecosystem-sensitive management measures.

### **1.7. Study scope.**

The research was conducted at four experimental sites and six fish landing sites on the Ugandan side of Lake Albert (**Figure 1.7-1**), focusing on *Engraulicypris bredoi* and *Brycinus nurse*, which are predominantly harvested using light-assisted fishing technologies such as solar bulbs, kerosene lanterns, and small seine nets. Lake Albert has 78 landing sites documented along the Ugandan shoreline (NaFIRRI, 2021); the six landing sites selected for this study were purposively chosen to be representative of the spatial, ecological, and operational diversity of the fishery. Specifically, the lake was stratified into three broad regions/zones (northern, central, and southern), with two landing sites sampled per zone, ensuring balanced spatial coverage across the lake.

The southern and northern regions are characterized by extensive shallow, vegetated littoral habitats and are strongly influenced by riverine inflows, namely the Semliki River in the south and the Murchison Nile–Albert Nile Delta system in the north, which support important breeding and nursery areas for small pelagic and other fish species. In contrast, the central region is dominated by steep escarpments and a large expanse of deep offshore waters, supporting distinct fishing strategies, gear deployment patterns, and habitat use. The four experimental fishing sites were established within this central region, as it encompasses the full gradient of habitats exploited by the SPS fishery, including deep offshore waters, shallow inshore zones, vegetated margins, rivers, and lagoon systems (Wandera and Balirwa, 2010; NELSAP, 2018; Hamilton et al., 2022),

thereby allowing controlled comparison of fishing depth, light use, and habitat-specific catch dynamics.

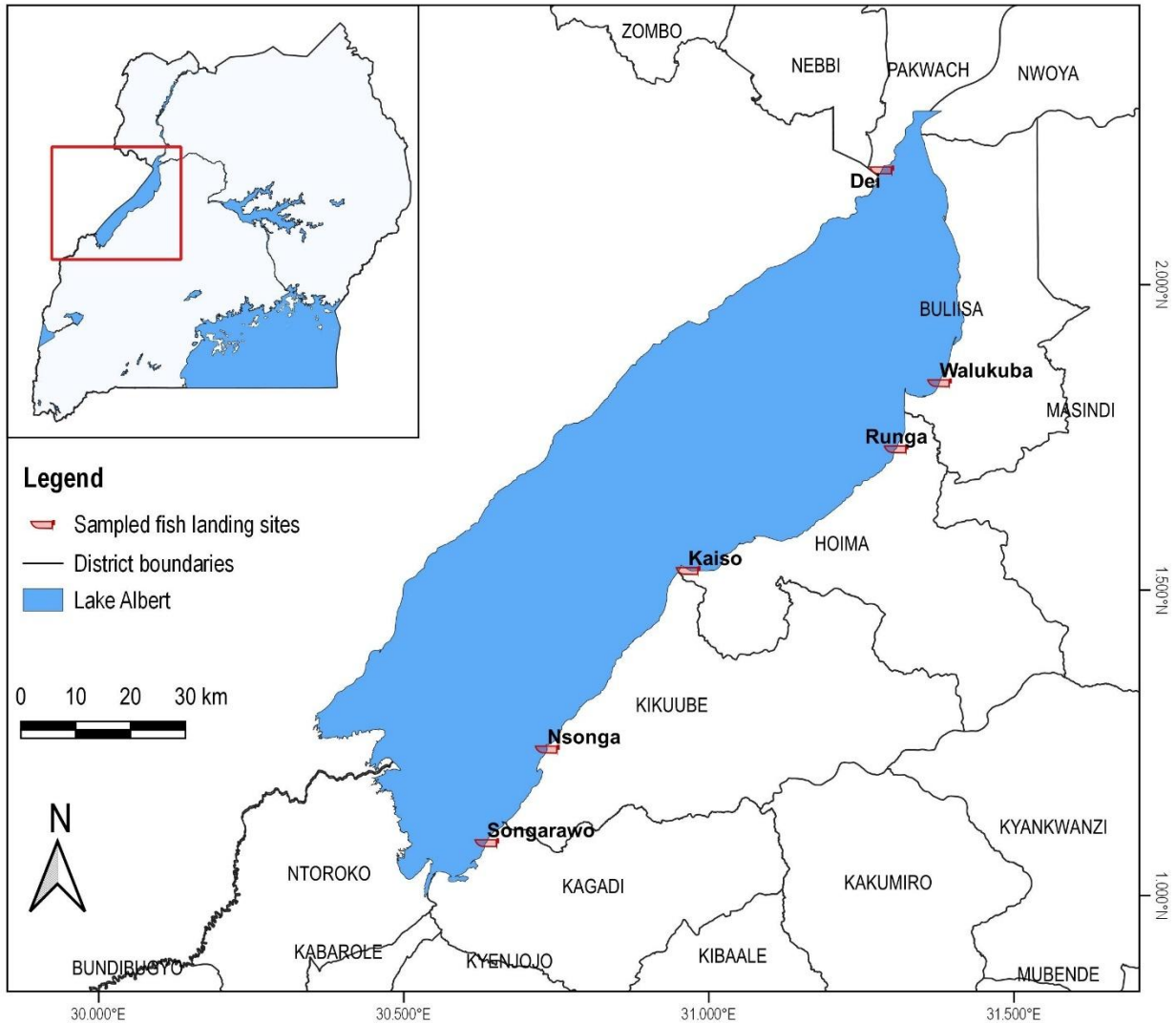


Figure 1.7-1. Map of Lake Albert indicating the landing sites sampled for commercial catch assessment surveys and community-based perception data collection.

Monthly fishery-dependent data collection was conducted at the selected landing sites to capture seasonal and temporal variability in catches and effort. In addition, historical catch and effort data from NaFIRRI archives were analysed alongside current observations to contextualize trends over time. For stakeholder and community perceptions data, three landing sites were selected, one per lake region (north, central, and south), to ensure representation of diverse ecological settings, fishing practices, and stakeholder interests across the entire Ugandan section of Lake Albert. This stratified and purposive sampling approach ensured that the study captured

spatial, ecological, and social heterogeneity while remaining logistically feasible and analytically robust.

## **1.8. Structure and organization of thesis.**

This PhD thesis is composed of nine chapters, structured to allow each chapter, except the first, third, and last, to stand alone as publishable journal articles. These chapters are either already published, under peer review, or being prepared for submission to peer reviewed journals. Cross referencing is used where necessary to maintain information flow and avoid repetitions. Each of the four chapters four to eight provides an abstract, introduction, materials and methods, results, discussion, conclusion and recommendations, and references.

**Chapter 1 - General introduction:** This chapter provides a comprehensive background to the fisheries sector, focusing on global, regional (Africa), and national (Uganda) contexts. It discusses significant shifts in the capture fisheries, particularly a transition from large-bodied species to small pelagic species-based fisheries in the African Great Lakes, with emphasis on Lake Albert in Uganda since the 1960s. The chapter also explores the emerging conflicts due to light fishing technologies and the challenges of managing a multi-species fishery. It concludes with the study's problem statement, objectives (both overall and specific), guiding research questions, study justification, and the thesis structure (this section).

**Chapter 2 - Literature review:** The chapter is based on a published manuscript titled "A review of light fishing on Lake Albert, Uganda: Implications for a multi-species artisanal fishery, published in journal of Fisheries Research, 258, 106535 (<https://www.sciencedirect.com/science/article/pii/S0165783622003125>).” The paper provides an extensive overview of the existing knowledge on small pelagic species and light fishing technologies. It discusses the dynamics of Lake Albert's artisanal fisheries, highlighting major shifts in catch species composition and fishing effort since the 1960s. The chapter identifies critical knowledge gaps that this study aimed to address to facilitate sustainable fisheries management on Lake Albert. This chapter formed a foundation upon which this study was designed.

**Chapter 3 - Overview of the methodological framework:** This chapter presents the research design, approach, study area, study population, and sampling strategy employed to address the five study objectives of this PhD research. The chapter provides an integrated overview of the methodological framework adopted to assess the socio-ecological impacts of artificial light-

assisted fishing targeting small pelagic species (SPS), *Engraulicypris bredoi* and *Brycinus nurse*, in Lake Albert, Uganda. Detailed methodological procedures are presented and elaborated under each specific objective in subsequent sections of the thesis.

**Chapter 4 to 8:** These chapters address the five specific objectives of the study, each focusing on key findings and their implications for managing SPS fishery in Lake Albert.

**Chapter four** explores stakeholder perceptions of light fishing technologies, the main source of conflicts on Lake Albert, and suggests management measures for sustainable fisheries and conflict resolution. The chapter is based on a published manuscript titled “Light-based small pelagic species fishing in Lake Albert: Divergent perceptions, conflicts, and implications for multispecies fishery management. *Journal of Great Lakes Research*, 102664. (10.1016/j.jglr.2025.102664)”.

**Chapter five** documents the spatial and temporal distribution of *E. bredoi* and *B. nurse* and the associated light fishing effort across Lake Albert, providing insights for management decisions. It examines trends in fishing effort (fishing gears, boats, and fishers), annual catch, and economic revenue of *E. bredoi* and *B. nurse* over a 15-year period (2007 up to 2022) and discusses the influence of lunar phases and fishing duration on catch rates.

**Chapter six** presents the life history traits and growth parameters of *E. bredoi* and *B. nurse*, including size at 50% maturity, length-weight relationship, mortality, recruitment, and condition factor across Lake Albert and how these can be leveraged to inform sustainable fisheries management. It compares population size structure across habitats, year months, and mesh sizes (legal size used in experimental sampling and illegal ones largely employed in artisanal fishers’ fleet). It also discusses the impact of non-compliance with legal sizes on target species stocks.

**Chapter seven** examines the effects of artificial light fishing technologies, specifically light type (solar and kerosene powered lights), light intensity, and stacking of small seine nets (net paneling) on target and bycatch species. The chapter is based on a published manuscript titled “Effects of artificial illumination and net panel configurations on small pelagic fisheries and bycatch on Lake Albert, East Africa. *Journal of Great Lakes Research*, 102690 (10.1016/j.jglr.2025.102690)”. It provides recommendations for optimizing SPS catch, minimizing juvenile bycatch of large species, and promoting co-existence and overall fisheries sustainability in a multispecies ecosystem.

**Chapter eight** presents the results of four stock assessment models (Virtual Population Analysis-VPA, catch\_MSU-Martell and Froese; 2012, Fox and Schaefer) used to establish growth parameters and biological reference points for *E. bredoi* and *B. nurse* in Lake Albert. The chapter discusses the implications of these findings for SPS management in Lake Albert and offers policy recommendations.

**Chapter nine: General discussion, conclusion, and recommendations:** This final chapter synthesizes the study's findings across all chapters and provides an overall assessment of the exploitation patterns and the socio-ecological dimensions of the SPS light fishery in Lake Albert. It concludes with key recommendations for sustainable fisheries management, addressing the needs of various stakeholders, including managers, researchers, policy makers, private sector industry, and fishing communities.

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## CHAPTER TWO: LITERATURE REVIEW

### CONTEXT

This chapter provides a comprehensive synthesis of documented literature on light-assisted fishing technologies in relation to the small pelagic species fisheries, focusing on the historical development, technological transitions, and current management status of light-assisted fisheries on Lake Albert. Historically, the lake's fishing industry was dominated by large-bodied species such as Nile perch (*Lates niloticus*) and tilapia. However, overfishing and environmental shifts have triggered a transition toward small pelagic species (SPS), specifically *Engraulicypris bredoi* and *Brycinus nurse*. The review highlights that while light fishing was introduced to exploit these abundant pelagic stocks, it has transformed the lake's socio-economic landscape, now contributing over 70% of the total catch by weight.

The review identifies the shift from traditional kerosene pressure lamps to modern solar-powered LED systems as a pivotal technological milestone. While kerosene lamps were associated with high operational costs, water contamination, and fire hazards, solar-LEDs offer a cleaner, more cost-effective, and technically efficient alternative. Despite these benefits, the literature underscores a significant "policy lag"; existing fisheries legislation in Uganda was largely designed for demersal gears (gillnets and longlines) targeting large-bodied species such as Nile perch and does not adequately address the unique dynamics of light-attraction technologies, such as the "vacuum effect" on juvenile fish and the resulting spatial conflicts between user groups.

Furthermore, the review situates Lake Albert within the broader context of the African Great Lakes, drawing parallels with the *Rastrineobola argentea* (Mukene) fishery of Lake Victoria. It notes that Lake Albert faces unique transboundary challenges, as the lack of accurate and adequate up-to-date scientific data, and non-harmonized regulations between Uganda and the Democratic Republic of Congo (DRC) complicates the enforcement of gear standards and closed seasons. This synthesis emphasizes that the sustainability of the SPS fishery depends on moving beyond "command-and-control" tactics toward an Ecosystem Approach to Fisheries Management (EAFM) that integrates technical gear restrictions with socio-economic incentives for fishers.

Ultimately, this chapter serves as the theoretical anchor for the dissertation, identifying the critical knowledge gaps, particularly in spatial effort distribution and stock-specific life history, that

the subsequent experimental and empirical chapters aim to fill. It argues that a science-informed, transboundary co-management framework is the only viable path to preventing the collapse of this vital multispecies resource.

The detailed literature review is presented below as published in *Fisheries Research*, 258, 106535 (<https://www.sciencedirect.com/science/article/pii/S0165783622003125>)



## Review

## A review of light fishing on Lake Albert, Uganda: Implications for a multi-species artisanal fishery

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## ABSTRACT

Lake Albert is one of the transboundary African Great Lakes, shared by Uganda and Democratic Republic of Congo. The lake supports a multi-species artisanal fishery, comprised of ~20 species, that vary in harvestable sizes. These range from small-sized fishes (<10 cm total length) such as *Engraulicypris bredoi* to large-bodied species such as *Lates niloticus* that can grow to 2 m in length. However, the abundance of large-bodied fishes has declined, leading to the emergence of a fishery around 2000, that targets small-sized pelagic species - SPS (*E. bredoi* and *Brycinus nurse*) using light. The aim of this article was to review the current understanding and identify important knowledge gaps in light fishing on Lake Albert, to inform sustainable fisheries management. Information was retrieved from Google Scholar, FishBase, IUCN, peer-reviewed articles, policy documents, and unpublished technical reports. We focused on light fishing effort, SPS catch, and their implications for a multi-species fishery. Transformations corresponding with light fishing introduction on Lake Albert from 2007 to 2021 include: (i) increase in number of boats and gears targeting SPS from 1632 to 1867 and from 1619 to 4929, respectively, (ii) three-fold increase in net panels per boat from 6 to 18, (iii) adoption of solar bulbs rather than kerosene lanterns, (iv) increase in annual lake catch from 144,900 to 348,536 tonnes, (v) shifts in catch composition from dominance of large-bodied species to currently SPS (~70%), and (vi) increase in proportion of fishing boats (~30%), and the lakeside population (60%) engaged in light fishery activities. Light fishing has also triggered fishing conflicts, mainly from competition for fishing areas and by-catch of juveniles of large species. We recommend a detailed scientific investigation of impacts of light fishing techniques on the lake fisheries, to inform on appropriate harvesting gears, fishing areas, fishing periods, and optimal fishing effort.

## 1. Introduction

Globally, capture fisheries play a critical role in the social, cultural, and economic development, providing food, employment, and income to millions of dependents (Cooke et al., 2016; Lynch et al., 2017; Van Anrooy et al., 2022). The production of capture fisheries has largely depended on large-bodied fish species, such as the large breams and carps of family Cyprinidae and perches (Perciformes). However, catch landings of the large species have declined in many fisheries, and the small pelagic species (SPS) that include anchovies, herring, mackerel,

sardines, cyprinids and clupeids, presently dominate capture fisheries production worldwide (Tacon and Metian, 2009; Van Anrooy et al., 2022).

Within the African Great Lakes such as Victoria, Malawi, Tanganyika, Kivu, and Albert, the SPS account for 40–80% of the total annual landings, depending on the water body and season (Kolding et al., 2019). The fishing pressure previously exerted on the large fish species, has shifted towards the SPS. This raises a major concern for the fisheries managers and scientists because the exploitation of SPS is taking place without comprehensive scientific evaluation of the fishery specific and

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ecosystem effects (Kolding et al., 2019). The SPG are perceived as resources with “low economic value” by fisheries managers, hence, they have received limited research and monitoring attention, leading to major gaps in our understanding of their full potential (Kolding et al., 2019). Further, given their small size, the SPG are inevitably harvested using unselective fishing gears such as small seine nets, that are made of small mesh sizes. These gears are considered illegal by most fisheries legislations aimed at protecting juveniles of the larger species. Consequently, the current capture techniques have led to conflicts between fishers and managers.

Two small pelagic species namely *Engraulicypris bredoi* (locally known as musiri) and *Brycinus nurse* (locally known as ragooge), dominate (>70 %) the lake-wide catch in Lake Albert, estimated at 395,490 tons in 2021 for both Uganda and DRC (NELSAP, 2021a). These species were previously targeted for manufacturing animal feed, but have increasingly become a major target for human consumption. They are harvested mainly during the moonless nights, using light attraction techniques that employ a light source (solar bulbs or kerosene lamps) and multiple small seine nets that are vertically joined together (Kolding et al., 2019; Mbabazi et al., 2019; NELSAP, 2021a,b).

The use of light fishing methods, particularly solar bulbs on Lake Albert has led to conflicts with fishers that target large-bodied fishes such as *Lates niloticus* (Nile perch), *Bagrus bajad* (Catfish), *Hydrocymus forskahlii* (Tiger fish), *Aleates baremoze* (Angara), and *Oreochromis niloticus* (Nile tilapia), that are mainly targeted using multifilament gillnets and long line hooks (NELSAP, 2021a,b). In addition to limited understanding of the effects of light fishing on other fish species, little is known about the biology and ecology of the target species, information that is key to guiding sustainable fisheries management, particularly of a multi-species fishery such as that of Lake Albert. In this review, we synthesize the current state of knowledge on light fisheries targeting SPG

of Lake Albert and identify important knowledge gaps. This review will form the foundation for the policymakers and development practitioners to design and implement sustainable management strategies for the Lake Albert multi-species fisheries.

2. Materials and methods

2.1. Study area

Within the African Great Lakes region, the transboundary Lake Albert (Fig. 1), shared by Uganda (54 %) and Democratic Republic of Congo – DRC (46 %) is Africa’s seventh largest lake. It is one of the few lakes that supports a multi-species artisanal fishery that is both subsistence and commercial (Von-Sarnowski, 2004; Mbabazi et al., 2012, 2019). The lake is located at the northern tip of the western branch of the Great East African Rift valley, at an altitude of 619 m above sea level (Ollier, 1990; NEMA, 2012). It has a surface area of 5500 km<sup>2</sup> and an average and maximum depth of 26 m and 58 m, respectively (Wandera and Balirwa, 2010). On the Uganda side, the lake is fed by two major inflowing rivers: River Semiliki in the south and the Victoria Nile at the northern tip, with the Albert Nile as the major outflow (Holden, 1963; Wandera and Balirwa, 2010). Lake Albert is a major source of water, employment, food, and income to the riparian communities (UBOS, 2019), with fishing as the primary economic activity.

2.2. Data acquisition

This article was based on a comprehensive review of existing literature and data on light attraction fishing techniques, with a specific focus on the Uganda portion of Lake Albert (Fig. 1 & 6), where light fishing is a major component of the multi-species commercial fisheries.

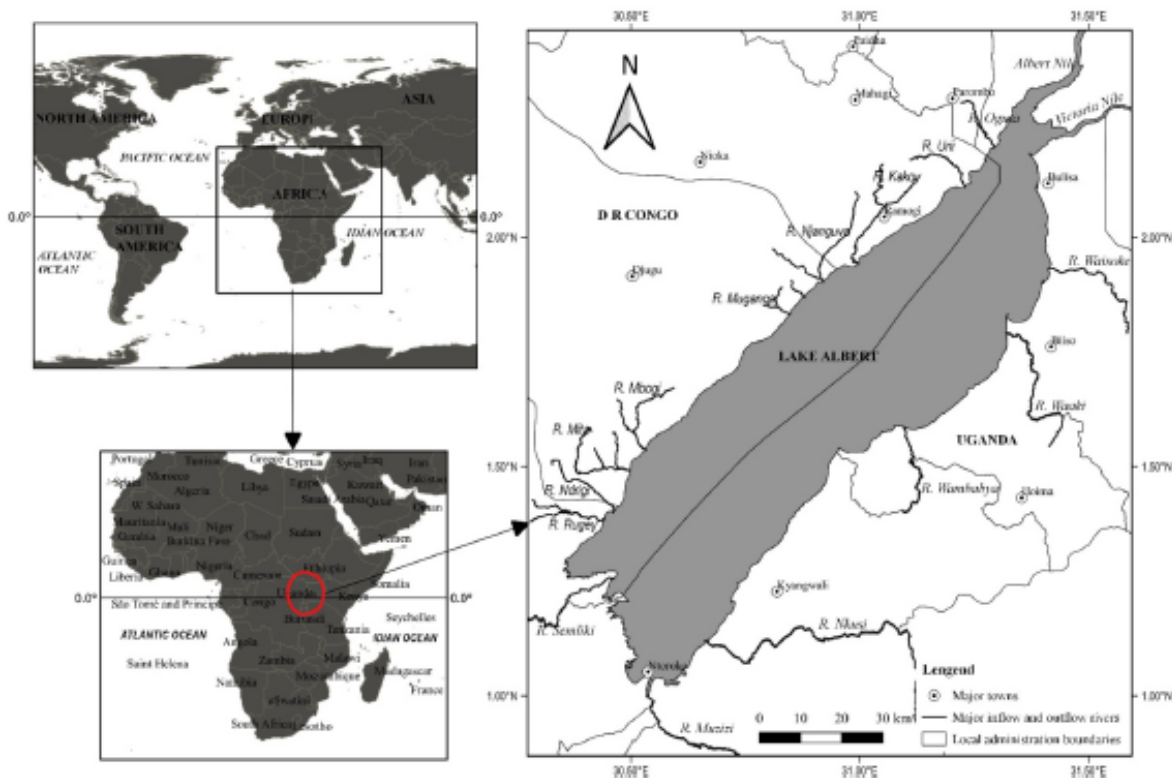


Fig. 1. Map showing the location of Lake Albert and the associated inflow and outflow rivers.

We retrieved 1260 information sources including policy briefs, statutory instruments, technical reports, preprints, PhD and Master theses, and peer reviewed articles from Google Scholar and FishBase (Fig. 2). The information searches were based on specific keywords including, *Engraulicypris bredoï*, *Brycinus nurse*, Lake Albert fisheries, kerosene light fishing, solar light fishing, small scale fisheries, and artisanal fisheries. The biological data on *E. bredoï* and *B. nurse* such as size at first maturity and feeding habits or modes and the geographical distribution were retrieved from FishBase (Paugy and Schaefer, 2007; FishBase team RMCA, 2021). Information on their conservation status was collated from the International Union for Conservation of Nature (<https://www.iucnredlist.org/>). Duplicates based on same authors, title, abstract summary, year of publication, and publishers that appeared in multiple search terms were removed. Additional filtering was based on the geographical scope, species, and type of light fishing technology. A total of 49 information sources (Fig. 2), which were within the study scope (geographical, species, and fishing method) were retained for detailed review. Additional information was retrieved from unpublished articles and technical reports (Worthington, 1929; Greenwood, 1976, 1966; Holden, 1963; Cadwalladr and Stoneman, 1966; Walker, 1972; Nyeko and Coenen, 1991; NELSAP, 2021a,b,c) policy documents including (Fish (Fishing) Rules, 2010), and information dissemination packages such as brochures.

### 3. Results and discussion

#### 3.1. Shifts in fishing effort variables on the Uganda portion of Lake Albert

Frame Survey (FS), the complete census of all landing sites and associated fishing effort variables on a water body, has remained one of the valuable sources of information needed for the fisheries management decisions on Lake Albert. Ideally, a FS should be conducted bi-annually, during which every landing site is visited once to enumerate

all fishing effort variables such as number of fishers, fishing boats, and fishing gears. However, because of logistical constraints, FS on Lake Albert have been inconsistent and limited. Records indicate that the traditional fishery on Lake Albert around the 1900s involved mainly simple local fishing gears including harpoons, woven reed baskets, and spears, but these progressively advanced to the use of gillnets (> 200 mm mesh size), seine nets, long-line and hand-line hooks (Worthington, 1929; Cadwalladr and Stoneman, 1966). The first Frame Survey (FS) on the Ugandan side of Lake Albert was conducted in 1950 to guide fishing boat licensing and focused on enumeration of fishing boats, with 497 fishing boats recorded (Nyeko and Coenen, 1991). Subsequent surveys in 1956, 1970, and 1971 showed an increase in fishing boats to 700, 826, and 985 respectively (Nyeko and Coenen, 1991). The later FSs of 2000, 2007, 2012, 2016, 2018, and 2021 (Table 2) were more comprehensive, focusing mainly on key variables of fishing effort such as landing sites, fishing boats, fishers, fishing gears, and gear sizes (Mbabani et al., 2012; NELSAP, 2021a,b,c). These surveys reveal a substantial increase in Uganda for the majority of fishing effort variables between 2007 and 2018 and a general reduction in these metrics in 2021 (Table 2). For example, the number of landing sites in Uganda increased from 72 to 102 (41.7 %) between 2007 and 2018 but declined to 78 in 2021; the number of fishing boats increased from 5764 to 9781 (69.7 %) between 2007 and 2018 but declined to 5075 in 2021, while that of fishers increased from 15,364 to 27,944 (81.9 %) between 2007 and 2018 and then declined to 13,999 in 2021. Over the same period, a similar trend was observed for illegal fishing gears such as monofilament gillnets, under-sized multifilament gillnets (< 102 mm), beach/boat seines, and cast nets (Table 2). In contrast, the number of small seine nets used in light fishing almost doubled from 1619 to 3076 between 2007 and 2018, with a further increase to 4929 in 2021 (NELSAP, 2021a). The majority (~99 %, Fig. 4) of small seines used on Lake Albert are below 8 mm, recommended as the minimum mesh size for harvesting *Rastrineobola argentea* (locally known as mukene in

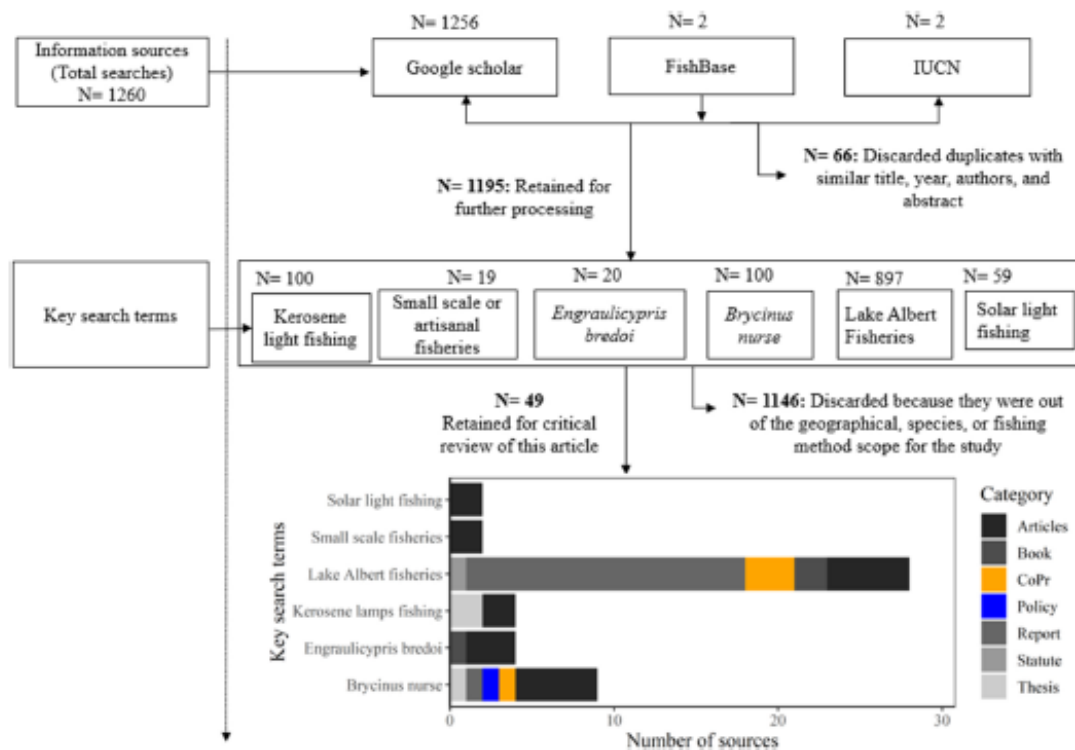


Fig. 2. Criteria used to access and prioritize literature used in this review.

Uganda and daaga in Kenya and Tanzania), a comparable small cyprinid in lakes Victoria, Kyoga, and Nabugabo (The Fish (Fishing Rules, 2010; Mangeni-Sande et al., 2018).

The observed increases in fishing effort variables, especially the illegal fishing gears between 2007 and 2018 could have been triggered by the need to increase catches of SPS. Indeed, the SPS catches doubled from 116,400 t to ~230,000 t (Mbabazi et al., 2012; NELSAP, 2021a,b) over this period. However, the reduction in key fishing effort variables, particularly of illegal status, between 2018 and 2021 can largely be attributed to the intensification of enforcement of fisheries regulations on the lake. Around 2017, Uganda took drastic measures to curb illegal, unreported, and unregulated (IUU) fishing practices on its territorial water by creating a Fisheries Protection Unit (FPU), a section of the Uganda People's Defense Force (UPDF). The FPU was first introduced on Lake Victoria in 2017 (Mponwenda et al., 2021), and later on Lakes Edward and George in 2018 (NELSAP, 2021b), Lake Kyoga in 2019, and on Lake Albert in 2021. Coinciding with the FPU deployment on Lake Albert were lake-wide joint enforcement patrols by the fisheries managers from Uganda and DRC, supported and coordination by the Lakes Edward Albert Integrated Fisheries and Water Resources Management (LEAF II) project. Both the FPU deployment and LEAF II joint patrols resulted in destruction of a number of illegal fishing effort (boats and gears) that were reported on Lake Albert during the 2018 FS (NELSAP, 2021b). Further, during the COVID-19 pandemic, the government of Uganda closed some landing sites on Lake Albert that were considered catalysts to the spread of the contagious virus. Additional landing sites were also involuntarily closed by the floods experienced on the Lake prior to the 2021 FS. Therefore, the effective enforcement coupled with restrictions due to the COVID-19 pandemic and floods could have contributed to the drastic decline in the illegal fishing effort in particular, on Lake Albert in the 2021 FS.

Fishers usually respond to declining catches with a suite of adaptive strategies that include a switch to more effective fishing gears, which in most cases are illegal, and an increase in fishing effort, particularly the gear units (Silas et al., 2020). Such strategies can lead to over-exploitation and potential collapse of the target stocks (Hjermann et al., 2004; Mugabe et al., 2021), hence the need for effective enforcement of the management measures. The drastic increase in illegal fishing effort indicators on Lake Albert, evidenced by the high concentration of fish landing sites along the lake shoreline (Fig. 1), the rampant increase of illegal gears, and the increase in the number of seine net panels could therefore be a pointer to weak enforcement of fisheries regulations even with the LEAF II project, as well as reduced abundance of target species, hence calling for strengthening enforcement through monitoring, control and surveillance.

### 3.2. Dynamics of fish catch composition on Lake Albert

Overall, there is a paucity of data on the fisheries of Lake Albert; however, previous studies do allow for a general temporal analysis of changes in the lake's fisheries. Until the 1990s, the commercial fishery in Lake Albert was entirely dependent on large-bodied species; *L. niloticus*, *B. bajad*, *O. niloticus*, and the moon fishes including *Ditrichodus niloticus*, *Citharus citharus*, *H. forskahlii*, and *Alestes baremose* (Worthington, 1929; Holden, 1963; Cadwalladr and Stoneman, 1966; Greenwood, 1966; Mbabazi et al., 2012). However, over-exploitation led to declines in fish stocks of the large species in Lake Albert (Von-Sarnowski, 2004; Mbabazi et al., 2012; Nakiyende et al., 2013). The lake has since experienced a shift in the commercial catch composition, from a dominance of large-bodied species to two SPS, namely *E. bredoi* and *B. nurse* (Kolding et al., 2019; NELSAP, 2019; Mbabazi et al., 2019; NELSAP, 2021a,b).

The traditional fishing on Lake Albert that started around the 19<sup>th</sup> century focused on simple fishing gears (Worthington, 1929). Some data collection on the lake catches started in 1920, following the formation of Uganda Game Department that was charged with the responsibility of

fisheries management in the country (Cadwalladr and Stoneman, 1966). Little work was done until trained officers were recruited in 1947 as part of the then British Colonial policy and posted to Lake Albert in 1949. The fisheries of Lake Albert expanded more rapidly in the late 1940's as a result of increased demand in the Belgian Congo (now Democratic Republic of Congo - DRC) market, but also reflected the greater use of gill-nets and long beach seines (3000 m), operated by Greek fishers from the present DRC. At the time, few native fishers could afford these effective fishing gears due to the prohibitive cost, and fishing was mainly confined to inshore shallow waters. The artisanal fishery at that time was comprised of ~20 fish species, dominated by *C. citharus*, *D. niloticus*, *L. niloticus*, and *L. macrophalmus* (Cadwalladr and Stoneman, 1966). The other harvestable species were: *O. niloticus*, *B. bajad*, *A. baremose*, *H. forskahlii*, *Gynodonis spp.*, and *Mormyrus spp.* The *C. citharus* population in Lake Albert started to show signs of stock decline around 1942, which was attributed to extensive use of beach seines (Cadwalladr and Stoneman, 1966). Thus, beach seines were prohibited and fishers encouraged to use the flux gillnets. Despite the limited catch records, it appears that the large-bodied species dominated the artisanal fishery until the 1960s (Holden, 1963; Cadwalladr and Stoneman, 1966). There is hardly any meaningful information on catch and effort on Lake Albert, for the period between the 1960s and late 2000s. Catch records (2007–2019) obtained through lake-wide Catch Assessment Surveys (CASs) indicate a drastic reduction in the relative composition of large-bodied species from ~100 % to < 30 % (Fig. 3) of the total lake catch over a three-decade period (1990s up-to-date). The substantial decline in the total lake catch in 2014 can be attributed to biases associated with timing of sampling. The 2014 CAS was conducted during the full moon phase (brightest night) of the month (Napirri, 2014). As already indicated above, the catch on Lake Albert is dominated by the two SPS *Engraulicypris bredoi* and *Brycinus nurse*, which are harvested mainly during the moonless nights. Hence, sampling during the full moon, with almost no fishing activity for the SPS consequentially affected the overall catches in 2014. This calls for a rational sampling design that takes into account the variability due to season and lunation.

While Lake Albert still supports a multi-species commercial fishery, there has been a switch to the dominance of SPS (*B. nurse* and *E. bredoi*), which constitute 60–80 % of the lake's annual catch (Fig. 3, Mbabazi et al., 2012; Kolding et al., 2019; Mbabazi et al., 2019; NELSAP, 2021a, b). Records also reveal a general increase in the overall annual catch on the Uganda side of the lake from ~144,900 t to ~340,000 t between 2007 and 2020 (Mbabazi et al., 2012; NELSAP, 2021a,b). The catch of large-bodied species is mainly comprised of juvenile fish (Mbabazi et al., 2012; NELSAP, 2021a,b), an indication of overexploitation that has substantially reduced their stocks. The catch per unit effort (CPUE), an alternative measure of species relative abundance (Malcom, 2001; Nyamweya et al., 2020), has also declined for the large-bodied fish species (NELSAP, 2021a,b). The increase in volume of *E. bredoi* and *B. nurse* in the commercial catches is likely reflecting the increase in fishing effort targeting these species and a reduction in predation pressure by the large-bodied species. The increase of SPS presents enormous potential for bridging the fish supply and per-capita consumption gaps; however, sustainability of this potential will depend largely on effective enforcement of science-based management measures and active involvement of fishers in resource management (Fig. 4).

### 3.3. Development of light fishing

Light fishing is a common method that has existed for centuries across the globe (Sahrhage and Lundbeck, 1967; Solomon and Ahmed, 2016; Nguyen and Winger, 2019), and has proven to be effective in catching SPS at night (Yami, 1976; Solomon and Ahmed, 2016). The technique is widespread in Africa, where it is used in harvesting SPS such as cyprinids, clupeids, sardines and herrings that contribute significantly to the total catch yield and economic value of most African fisheries (Nguyen and Winger, 2019). Light fishing developed from an

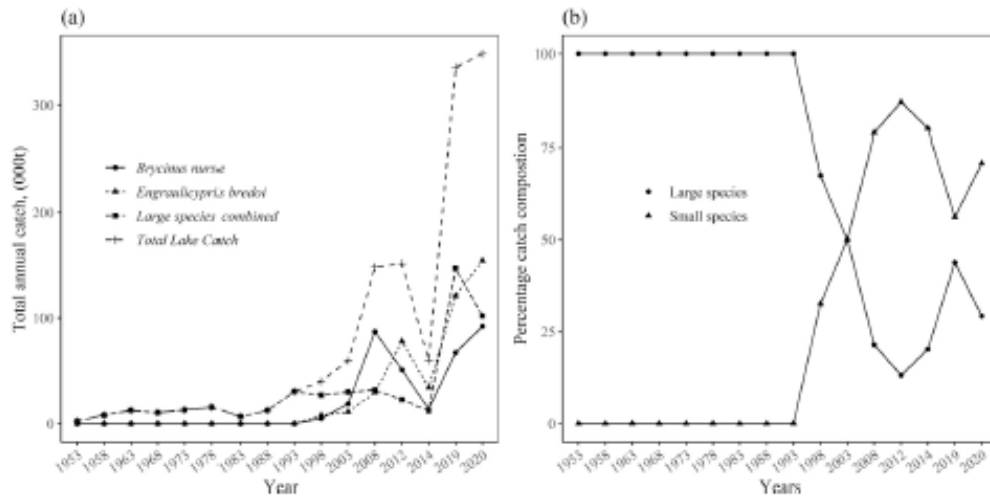


Fig. 3. Changes in commercial catch composition on the Uganda portion of Lake Albert (1953 – 2019). Data modified from FAO, 1989, Mbabazi et al., 2012, and NaFIRRI unpublished data.

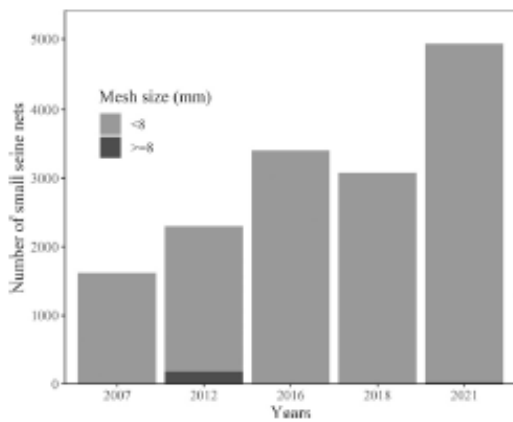


Fig. 4. Trends in the number of small seines used on Lake Albert between 2007 and 2021 (Modified from NELSAP, 2021c Frame Survey Technical Report).

observation that fish were attracted to the lake shores illuminated by camp fires (Nguyen and Winger, 2019). The method slowly advanced to the use of movable torches, and later, the oil/ kerosene/ gas lanterns/lamps floated on water. Currently, powerful light attraction devices such as incandescent, fluorescent, led, metal halide, Light Emitting Diode (LED), and solar bulbs are in use (Yami, 1976; Mills et al., 2014; Solomon and Ahmed, 2016).

On the African Great Lakes, light fishing has its origins on lakes Tanganyika and Malawi, where it was introduced to target the two clupeids (*Stolothrissa tanganyicae* and *Limnothrissa miodon*) and the cyprinid *Engraulicypris sardella* (locally known as Usipa), respectively. Both species still account for ~50 % of the landed catch on these lakes (Kolding et al., 2019). Light fishing was subsequently introduced to other lakes in the region. On Lake Kivu, the technique was introduced to harvest *Limnothrissa miodon*, which accounts for 75 % of the annual catch (Muderhwa and Matabaro, 2010; Mgana et al., 2019). In Uganda, light fishing was first introduced into Lake Victoria in the early 1970s (Table 1), targeting *R. argentea* (Wanders, 1990). The technique later spread to Lake Kyoga in the 1990s; Lake Albert in early 2000s (Namboose, 2008; NaFIRRI, 2012), and Lake Nabugabo around 2009 (Groves et al., 2021). Light fishing involves the use of light (kerosene lamps

**Table 1**  
The period of emergence of light fishing for the Small Pelagic Fishes (SPF) on Ugandan lakes (Source: NaFIRRI, 2012; Kolding et al., 2019). Target species are those fish that were the focus of the fishery at the time the light fishing for SPF was initiated.

Year	Lake system	Target species	Small pelagic fishes
1970s	Victoria	Tilapia, <i>Clarias</i> spp, and <i>Bagrus</i> spp	<i>R. argentea</i>
1994	Kyoga	Nile tilapia and Nile perch	<i>R. argentea</i>
2002	Albert	<i>A. baremose</i> , <i>H. forskahlii</i> , Nile perch	<i>B. nase</i> and <i>E. bredoi</i>
2009	Nabugabo	Nile perch and Nile tilapia	<i>R. argentea</i>

and/or solar bulbs) and an encircling small seine net (commonly referred to as a lampara net). For consistency in this article, the former name will be used. A single small seine net usually measures 100 m in length and 2 m in width. When many seine net panels are joined vertically with hauling ropes attached to both ends, they constitute an encircling fishing net (Fig. 5). Light fishing was initially out-lawed in Uganda by the Fish and Crocodile Act (Fish Act, 1951), but was later permitted under the current fishing regulations (Fish (Fishing) Rules, 2010), despite the absence of conclusive scientific information to guide its operation.

Light fishing on Lake Albert started with use of kerosene lamps and small seine nets (NaFIRRI, 2012). On a single fishing night, each boat used a single net comprised of 4–6 net panels, that were vertically joined into a single fishing unit and a maximum of four kerosene lamps. Around 2016, the technique advanced to the adoption of solar bulbs to replace the kerosene lamps as the primary source of light (Plate 1). This was accompanied by a corresponding increase in the light fishing effort (boats, net panels, and lamps) targeting SPG. As examples, the number of fishing boats targeting SPG increased by 88 % from 1632 in 2007 to 3069 in 2018, and then declined to 1867 in 2021 (Table 2). The total number of small seine nets operated on the lake also progressively increased from 1619 in 2007 to 4929 in 2021 (Table 2, Fig. 4). Currently, a single unit of small seine net used in each fishing boat targeting SPG is comprised of 12–20 panels. The majority of small seine nets used on Lake Albert are below 8 mm of mesh size (NELSAP, 2021c), that is prohibited (Fish (Fishing) Rules, 2010). The increase in net paneling could be driven by the need to exploit the deep open waters to increase catch. The deep open waters are also areas of operation for fishers targeting large species, hence may underly, at least in part, recurring

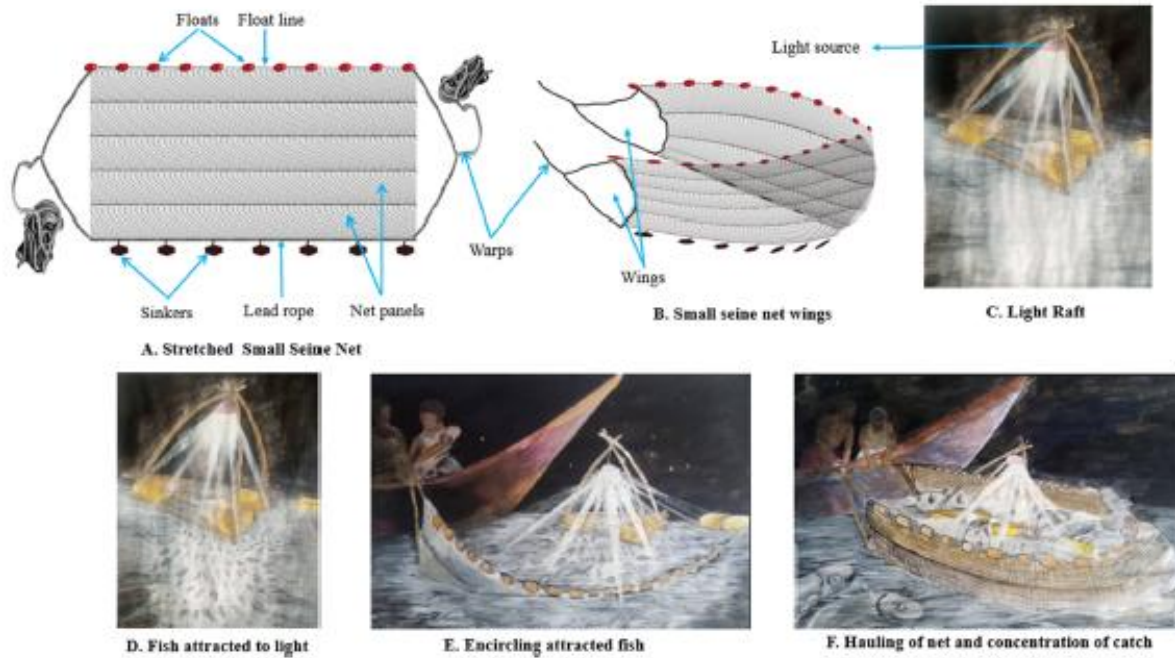


Fig. 5. (a-f). Illustration of small seine net, light raft and light fishing operations.



Plate 1. Light fishing effort at Kaiso landing site, Lake Albert, Uganda: fishing boats and gears (a), solar bulbs and floats (b), solar bulbs and small seine nets spread on shore to dry after a fishing trip (c & d). Photo credit: Mr. Nakiyende Herbert, February, 2020.

conflicts. This highlights the need for gear selectivity and light attraction studies to determine the optimal mesh size and light for the SPS in Lake Albert.

#### 3.4. Operation of a typical light fishing gear and targeted species for light fishing in Lake Albert

The light fishing setup involves attaching a light attraction device(s) (hurricane or incandescent lamps, bulbs, metal halide lamp) to a firm structure (raft), that is floated on the lake surface to attract fish (Fig. 5a-e). The fish concentrate around the illuminated area and are scooped out

**Table 2**  
Trends of key fishing effort indicators on Lake Albert, Uganda. (Extracted from (NELSAP, 2021c) Frame Survey Technical Report). \*\* The legal status is based on the Uganda fishing regulations (Fish (Fishing) Rules, 2010).

Fishing effort indicator	Legal status**	Period				
		2007	2012	2016	2018	2021
Landing site		72	72	78	102	73
Fishers		15,364	15,424	23,722	27,944	13,999
Fishing boats		5764	6216	8672	9781	5075
Boats using perforated basins	illegal	32	33		40	30
Boats using beach seine nets	illegal	44	22	223	228	124
Boats using boat seine nets	illegal			94	329	83
Boats using cast nets	illegal	81	116	414	354	182
Boats using multifilament gillnets	legal if ≥ 4 in.	2192	2616	2026	2232	1049
Boats using hand-lines	legal if size ≤ 9	14	24	52	36	91
Boats using long-lines	legal if size ≤ 9	1520	527	908	948	651
Boats using monofilament gillnets	illegal	196	519	1349	2123	644
Boats using other gears	illegal			35	14	
Boats using small seine nets	legal	1632	2303	3412	3069	1867
Boats using basket traps	illegal	53	56	159	408	354
<b>Gear types</b>						
monofilament gillnets	illegal		3774	6075	22,886	6098
multifilament gillnets < 4 in.	illegal	54,350	102,457	84,206	57,237	19716
multifilament gillnets ≥ 4 in.	legal	42,365	42,374	13,184	16,325	45,044
Total Gillnets		96,715	144,831	97,390	73,562	64,760
longline hooks ≤ 9	legal					353,605
longline hooks > 9	illegal					1054,643
Total longline hooks		1965,576	745,706	1699,380	1854,706	1408,248
Beach seine nets	illegal	44	22	73	291	83
Boat seine nets	illegal			94	338	182
Cast nets	illegal	81	125	429	453	1761
Hand-line hooks	Legal if size ≤ 9	746	447	13,266	310	1944
Basket traps	illegal	655	745	2037	7771	6509
Scoop nets	illegal				47	10
Small seine nets (< 8 mm mesh size)	illegal	1619	2122	3403	3077	4905
Small seine nets (≥ 8 mm mesh size)	legal		175	3	2	24
Total Small seine nets		1619	2297	3406	3079	4929

using a variety of gears, usually an encircling seine net. The fishing with an encircling gear, in this case a small seine net, is usually performed by 2 – 3 crew (fishers) on a single fishing vessel unit, to target the SPS such as *R. argentea*, *E. bredoi*, and *B. nurse*. The target species usually move in schools close to the water surface, and feed mainly on zooplankton (Mills et al., 2014). Once the shoal of fish has concentrated around the illuminated zone, an encircling gear (small seine net) is then surrounded around the light raft, and the two wings of the net are hauled at the same time to concentrate the catch. A detailed illustration of light fishing gear component and fishing operations is presented in Fig. 5a-f. The main impact of this gear category is occasional bycatch/discards, in particular when the net is used in association with a fish aggregating device (FAD).

Marchean et al. (2005) suggested that the light primarily attracts small aquatic organisms such as zooplankton and insects, which are prey for the SPS. The attracted small organisms in turn entice the SPS to congregate in schools to feed. The large species that prey on SPS is also attracted to follow their prey. During the encircling and hauling process, both the SPS and their predator (bycatch) are trapped in the fishing gear.

Before the introduction of light fishing on Lake Albert, *E. bredoi* was never harvested, while *B. nurse* was harvested on a small scale by women who could wade through the inshore shallow waters, using perforated basins or baskets baited with fish or local brew (locally known as malwa) dregs or waste (NaFIRRI, 2012). However, as the light fishery developed on Lake Albert, it was noted that *B. nurse* was also captured in substantial quantities of up to 30% alongside *E. bredoi*, and hence was considered a target of the light fishing technologies. Other than light, *B. nurse* is also landed in gears prohibited on Lake Albert (Fish (Fishing) Rules, 2010), such as small gillnets of 40–50 mm stretched mesh size, monofilament gillnets, and beach/boat seines (Table 3). These gears contribute 20–40 % of the species' total annual catch (NELSAP, 2021a, b). In addition to the SPS, substantial quantities of juveniles and adults of other large-bodied fish species are also captured in the light fishing gears. This has sparked conflict with other fishers, mostly those targeting

**Table 3**  
Catch Per Unit Effort – CPUE (Kg/Boat/Day ± SE) of *Brycinus nurse* and *Engraulicypris bredoi* landed in the different fishing gears on Lake Albert (Uganda) between 2019 and 2020.

Year	Fishing gear category	CPUE (Kg/Boat/Day) ± SE	
		<i>B. nurse</i>	<i>E. bredoi</i>
2019	Beach seine net	98.0 ± 15.0	
	Boat seine net	36.8 ± 7.7	
	Small mesh size gillnet	23.0 ± 2.9	
	Monofilament gillnet	37.8 ± 2.5	
	Small seine net	66.8 ± 11.8	171.7 ± 6.6
2020	Small mesh size gillnet	50.4 ± 10.2	
	Monofilament gillnet	48.9 ± 4.2	
	Small seine net	132.3 ± 6.5	229.1 ± 12.0

large species such as the Nile perch, as some of the bycatch is comprised of juvenile Nile perch.

**3.5. Description of biological and ecological characteristics of *E. bredoi* and *B. nurse* in Lake Albert**

Little is known about the biology, ecology, and life-history characteristics (age/size at maturity, growth rates, maximum size, maximum age, fecundity, and egg size) of *E. bredoi* and *B. nurse* in Lake Albert. Such information is critical to the formulation of ecosystem based management strategies (King, 1995; Malcom, 2001). Here, we summarize the current state of knowledge of the biology and ecology of both species. *Engraulicypris bredoi* (Plate 2a) is a small silver pelagic zooplanktivorous species of the family Cyprinidae and is endemic to Lake Albert (Greenwood, 1966; Howe, 1984; Riddin et al., 2016; Wandera and Balirwa, 2010; FishBase team RMCA, 2021). The species grows up to 45 mm in total length - TL (Hontela and Stacey, 1990) and is known to inhabit the

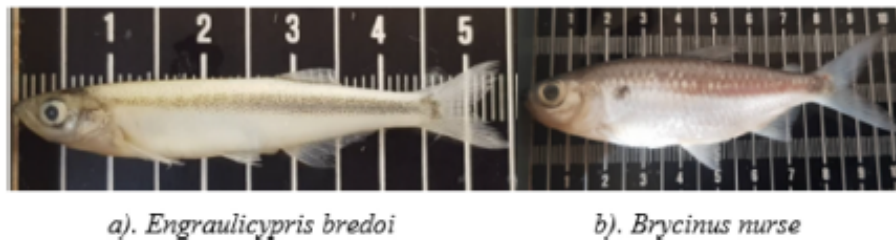


Plate 2. Target species of light fishing on Lake Albert, Uganda. (Photo credit: Mr. Mulwoza Alex, NaFIRRI, November 2021).

shallow and deep water habitats. It is also categorized as vulnerable by the IUCN Red List of Threatened Species (Narugonza and Musinguzi, 2022). *Brycinus nurse* (Plate 2b) is a silvery pelagic species of family Alestidae, that can grow up to 250 mm in total length (TL). The species is widespread in West African waters, The Nile River, and Lake Albert (Greenwood, 1966; Bailey, 1994; Saliu and Fagade, 2003; Getahun, 2007) and categorized as least concern under the IUCN RedList (Lalèyè, 2020). *Brycinus nurse* is omnivorous, feeding on zooplankton, water shrimp, insects, snails, and vegetation (Bailey, 1994; Paugy and Schaefer, 2007). The species also serves as prey for the larger-bodied piscivores including *L. niloticus*, *B. bojad*, *Barbus bynni*, and *A. baremose* (Wandera and Balirwa, 2010). Current information on the key biological characteristics such as species population structure, size at maturity, fecundity, distribution, abundance, stock biomass, spatial and temporal variations, and inter-species interactions for both *E. bredoi* and *B. nurse* in Lake Albert is lacking, but critical to informing policy and management decisions (King, 1995; Fromentin and Fonteneau, 2001; Mace, 2001; Sharpe et al., 2012).

### 3.6. Controversies of light fishing on Ugandan portion of Lake Albert

Light, the main technique for fishing *E. bredoi* and *B. nurse* on the Uganda portion of Lake Albert (Uganda), is completely prohibited in DRC. Using the technique, particularly solar bulbs on the Uganda portion of Lake Albert has triggered conflicts with fishers targeting the large-bodied species, especially Nile perch (NaFIRRI, 2012). The conflicts are fueled by competition for fishing grounds, unregulated fishing effort for *E. bredoi* and *B. nurse* (Fig. 6; Plate 1), and high bycatch that is dominated by juveniles of Nile perch, *A. baremose* and *B. bojad*. Conflicts among fisheries stakeholders are common (Salayo et al., 2006; Dahlet and Sánchez Lizaso, 2021), and they arise from differences in power, interests, values, priorities, manner of resource exploitation, and institutional failures in managing fisheries and enforcing laws and regulations (Murshed-e-Jahan et al., 2014). For example, resource use conflicts have been reported between the artisanal and shrimp bottom trawl fisheries in Kenya's Malindi-Ungwana Bay (Munga et al., 2014) and between small-scale and industrialized fishers in the Indian Coromandel Coast (Bavinck, 2005). Resolving such conflicts entails a clear understanding of the dynamics and social-ecological interactions of the exploited stocks. In some fisheries, fishing conflict has been resolved through closed seasons and closed areas (Murshed-e-Jahan et al., 2014).

On water bodies elsewhere, light fishing techniques have proved convenient, environmentally safe, time saving, and cost-effective, with better catches than the traditional kerosene lanterns (McHenry et al., 2014; Mills et al., 2014). However, these techniques are often associated with greenhouse gas emissions (via kerosene lamps), overfishing, high bycatch, and plastic pollution (Nguyen and Winger, 2019). There has never been a detailed study to assess impacts of light fishing on Lake Albert and in Uganda as a whole, to inform sustainable management of the SPS light fisheries. A one-off mapping of distribution of light fishing effort on Lake Albert conducted in 2020 revealed widespread concentration of light on the Uganda portion, during the moonless nights (Fig. 6). Studies by Lowry et al. (2007) and Poisson et al. (2010) have

shown that lunar phase influences the distributions and behavior of aquatic organisms. However, no study has investigated relationships between catch and lunar phases on Lake Albert, information that is vital for management decision tools such as possible fishing holidays (closed fishing periods) on the Lake.

### 3.7. Previous research and measures to guide light fishing in Uganda

Initial efforts to guide light fishing started in the 1990s on Lake Victoria (Wandera, 1990), where *R. argentea* is a major target for light fishing. Small seine nets of 8–10 mm and a maximum of four hurricane kerosene lamps were recommended to harvest the species in waters > 2 km from shoreline, to protect juveniles and breeding stocks of the target and non-target species. Later studies on the lake (Mangeni-Sande et al., 2018) observed a reduction in mean size (length) of *R. argentea*, which was attributed to non-compliance by the fishers to the earlier recommendation. The study observed that fishers had shifted from the 8–10 mm seines to majorly < 5 mm, doubled seine net panels from between six and eight to 12–20 panels per boat, and adopted solar lamps. On Lake Albert, the National Fisheries Resources Research Institute (NaFIRRI) recommended four panels of small seines (8–10 mm) and four kerosene lamps per boat, as a precautionary management measure for the light fishing (NaFIRRI, 2012). This was based on the catch and fishing effort data for *E. bredoi* and *B. nurse* (2007–2008) (Mbabazi et al., 2012). A more comprehensive study was recommended, to quantify the biological and ecological characteristics of SPS and effects of light harvesting methods on their stocks to inform long-term management decisions. However, fishers in Lake Albert quickly shifted to using solar bulbs and progressively increased net panels by almost four-fold in attempt to increase catches. This has escalated conflicts among fishers following a petition from the Nile perch fishers, who continue to protest the use of light fishing on Uganda waters. Consequently, the use of solar light fishing in fishing was banned by H.E the President of the Republic of Uganda in 2018. Despite the ban, fishers continue to stealthily use solar bulbs to harvest *E. bredoi* and *B. nurse* in Lake Albert. There is therefore, need for comprehensive investigation of light fishing methods on Lake Albert, to understand their impacts at ecosystem level to inform the long-term sustainable management measures such as catch and effort limits, fishing grounds, and fishing seasons in a multi-species setting of Lake Albert.

### 3.8. Post-harvest handling, processing, and marketing of *E. bredoi* and *B. nurse* on Lake Albert

Both *E. bredoi* and *B. nurse* are harvested during the night, and the catch is variously processed during the day. *Engraulicypris bredoi* is exclusively sun-dried on platforms, including raised racks, rocks, and bare ground mixed with sand (Kolding et al., 2019). *Brycinus nurse* is sun-dried as above, but also deep fried and sold as snacks. The processed sun-dried fish is sold for either animal feeds or human consumption, with some exported to the neighboring countries, majorly the DRC and South Sudan (Kolding et al., 2019). Although *B. nurse* and *E. bredoi* now dominate the Lake Albert fisheries by volume, their economic share of

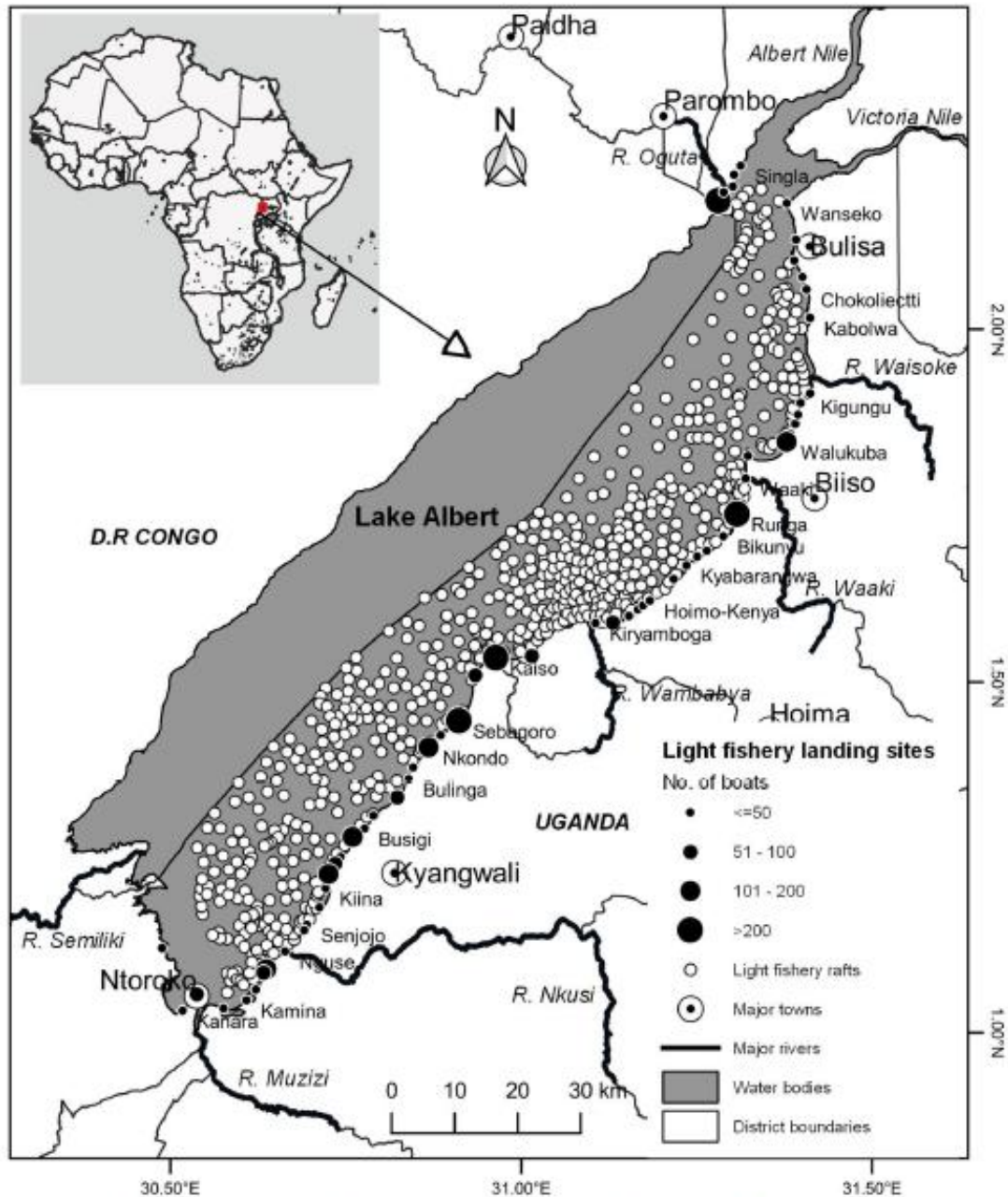


Fig. 6. Map of Lake Albert showing distribution of light fishing effort targeting *Brycinus nurse* and *Engraulicypris bredoii* on the Uganda portion of the lake in 2020.

the annual revenue is < 20 % (NELSAP, 2021a), with the underlying causes not well documented. However, facilities for post-harvest handling and processing of small fishes on Lake Albert are still inadequate, with the largest volume of the catch processed on bare ground where it is exposed to numerous contaminants and post-harvest losses, thus rendering it unfit for human consumption. For example, Ofoyo (2021), documented losses of 10–43 % in *E. bredoii* alone. The current efforts to improve the handling and processing of SPS using a solar tent dryer under the IDRC/ACIAR-funded-NutriFish project should be strengthened and upscaled to improve their quality for human consumption.

#### 4. Conclusion and recommendations

This review shows that both *E. bredoii* and *B. nurse* have become the major species of the Lake Albert commercial fishery. These SPS have enormous potential to bridge the fish supply gap and the per-capita consumption deficits to improve nutrition in low-income populations, mainly because they are abundant, affordable, highly nutritious (consumed whole), and have a wide distribution and long shelf-life when well processed. However, this potential is hampered by social, technical, legal, and policy constraints, thus exacerbating the conflicts among the different resource user groups on the lake. There is limited

knowledge of the stock dynamics and appropriate light harvesting technologies for the SPS to inform their sustainable management in Lake Albert. Therefore, attaining the full potential of SPS and sustainability of the multi-species fisheries in Lake Albert will require an ecosystem approach to fisheries management. This demands a comprehensive stock assessment of the SPS to understand their stock dynamics, ecological interactions with the diverse lake species, and impacts of current light harvesting techniques. Specifically, studies should provide data to facilitate recommendations on i) appropriate fishing gears, net panels, light sources, and light intensity; ii) optimal number of fishing boats, iii) suitable fishing areas, allowable catch, and iv) fishing periods and seasons for the SPS. In addition, underlying factors to the low economic contribution of the SPS, despite dominating fish catches in the lake need to be addressed through development of innovations for value addition and mitigation of post-harvest losses and wastage to fully harness their potential contribution to food and nutrition security.

#### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Data availability

The authors have adequately cited and referenced all sources of secondary data and information used in this review within the main body and reference section of the article.

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## **CHAPTER THREE: GENERAL METHODOLOGY**

This section provides the overarching methodological framework guiding the study, while detailed methodologies corresponding to each specific objective are presented in the respective chapters aligned to specific objectives of the study.

### **3.1. Research design**

This study employed a mixed-methods research design, quantitatively dominant, to collect and integrate both qualitative and quantitative data (Creswell, 2014; Grover, 2015). This design enables comprehensive analysis by allowing triangulation, enhancing the validity of findings, and addressing the research problem from multiple perspectives (Creswell & Tashakkori, 2007; Maxwell, 2016). The combination of methodologies helps to bridge gaps in understanding that might exist when using either approach in isolation.

### **3.2. Research approaches**

Both deductive and inductive reasoning approaches were adopted (Ali & Birley, 1999). The deductive approach was used in the testing of hypotheses based on existing theory and previous studies, while the inductive approach enabled the exploration of new insights from qualitative data, especially regarding community perceptions and undocumented fishing practices.

### **3.3. Description of study area**

The research was conducted in the Ugandan portion of Lake Albert (see **Figure 1.7-1**), a transboundary water body shared between Uganda (54%) and the Democratic Republic of Congo (46%). Situated in the northern end of the western rift valley (between latitudes 1°01'N and 2°21'N, and longitudes 30°32'E and 31°28'E), Lake Albert lies at an elevation of 618 meters above sea level, with a surface area of approximately 5,270 km<sup>2</sup> and a mean depth of 25 meters (NEMA, 2012). In Uganda, Lake Albert borders the districts of Pakwach, Buliisa, Hoima, Kikuube, Kagadi, and Ntoroko. It receives inflow from several rivers including the Semliki, Kafu, Muzizi, Nkusi, Wambabya, Waaki, and the Victoria Nile, with the Albert Nile serving as the main outflow.

Ecologically, Lake Albert has been characterized into four major habitats: shallow inshore areas, lagoons and large bays, river inlets, and deep offshore waters (Holden, 1963; Wandera & Balirwa, 2010). Recent fishery surveys have further stratified the lake into three zones: northern,

central, and southern, based on ecological and fishing patterns (Mbabazi et al., 2012; NaFIRRI, 2012a; Kabir, 2016; NaFIRRI, 2019).

In this study, the lake was stratified into inshore (shallow, vegetated, and river-influenced habitats) and offshore (deep open-water habitats) ecological zones (Section 3.3), recognizing that light fishing occurs across both zones but may produce different catch compositions and size structures. Six landing sites and four experimental sampling sites were purposively selected, encompassing inshore and offshore zones, to reflect areas of high light-fishing activity across the lake's ecological gradients. Site selection was informed by historical catch records (Mbabazi et al., 2012; NaFIRRI, 2012), prior bathymetric surveys (Hamilton et al., 2022), and consultations with fisheries officers and local fishers to ensure that sampling locations represented the diversity of fishing grounds where light attraction is actively used.

### **3.4. Study population**

The study focused on two small pelagic species (SPS), *Brycinus nurse* and *Engraulicypris bredoi*. Quantitative data were obtained through experimental fishing trials conducted at four lake stations and from commercial catches sampled at six lakeshore landing sites where light-assisted fishing was actively practiced. These sites were selected to capture spatial and operational variability in SPS harvesting across the lake.

The qualitative component targeted members of the fishing communities operating at the selected landing sites, including fishers and other key stakeholders, who were purposively selected to provide insights into perceptions, practices, and experiences related to light-assisted fishing technologies. Parameters measured from experimental fishing and commercial catch assessments included species composition, catch quantities (by weight), types and intensity of light sources used, net configurations, and key life-history characteristics of the target species, including length, weight, maturity stage, and fecundity. Together, these data supported integrated analysis of exploitation patterns, gear performance, and biological responses of the SPS fishery.

Given that light-assisted fishing occurs widely across Lake Albert and spans multiple ecological zones, *Engraulicypris bredoi* and *Brycinus nurse* were assumed not to occupy identical habitats uniformly across the lake. Rather, they were treated as co-caught species whose spatial overlap is mediated by fishing technology, depth, seasonality, and habitat accessibility. Given the

mobility of light-based fishing units and their documented deployment in both inshore and offshore waters, the study adopted a stratified ecological sampling approach to capture this heterogeneity.

### **3.5. Sampling strategy and data collection framework**

The study adopted a mixed-methods research approach, integrating complementary qualitative and quantitative techniques to comprehensively assess exploitation patterns, ecological responses, and governance dimensions of the Lake Albert small pelagic species fishery. Mixed-methods designs are particularly suited to complex fisheries systems, as they enable triangulation of ecological data with socio-economic and institutional insights (Creswell & Plano Clark, 2018).

Data collection employed a proportionate stratified sampling strategy (Etikan & Bala, 2017), with sampling intensity aligned to observed fishing effort within each ecological zone. Quantitative fishery-dependent data were collected monthly over a 24-month period to capture seasonal and lunar variability, while qualitative data were collected once using a cross-sectional design through interviews and focus group discussions with fishers and key stakeholders at selected landing sites. This approach ensured that the widespread spatial deployment of light fishing across the lake was explicitly accounted for, rather than implicitly assumed.

A systematic literature review was first undertaken to synthesize existing knowledge on small pelagic fisheries, light-assisted fishing technologies, and ecosystem-based fisheries management, and to identify key knowledge gaps relevant to Lake Albert. This resulted in a peer-reviewed publication: “A review of light fishing on Lake Albert, Uganda: implications for a multi-species artisanal fishery (Fisheries Research, 258, 106535)”.

Key Informant Interviews (KIIs), defined as semi-structured interviews with individuals possessing specialized knowledge such as fisheries officers, BMU leaders, and experienced fishers, were conducted to capture expert insights on fishing practices, governance arrangements, and emerging management challenges (Kumar, 2014). These were complemented by Focus Group Discussions (FGDs), which are structured group interviews used to elicit shared perceptions, norms, and conflict dynamics among fishers and other stakeholders.

Quantitative fishery-dependent data were collected through Catch Assessment Surveys (CAS), which involve systematic sampling of catches at landing sites to estimate catch composition, effort, catch rates, and size structure over time (FAO, 2016). Frame Surveys (FS), periodic censuses of fishing units, gears, and vessels, were used to quantify fishing capacity and effort distribution,

providing the sampling frame for CAS and supporting effort standardization (FAO, 2015). To assess fish distribution independent of catches, hydroacoustic surveys were conducted. These use scientific echosounders to estimate fish abundance, vertical distribution, and spatial patterns in the water column, particularly useful for small pelagic species (Simmonds & MacLennan, 2005).

Spatial dynamics of fishing pressure were further examined using geospatial mapping of night-time fishing effort, which combined GPS tracking and spatial analysis to map the distribution and intensity of light-assisted fishing across ecological zones. In addition, experimental fishing trials were undertaken to evaluate the effects of gear configurations, light types, and fishing depth on catch composition and size selectivity under controlled conditions.

Finally, statistical and modelling approaches, including generalized linear models and bio-ecological analyses, were applied to quantify relationships between fishing effort, environmental proxies, and biological responses, thereby supporting inference and management-oriented decision-making.

### **3.6. Objective-Specific Methodologies**

*Objective 1: Evaluate stakeholder perceptions of artificial light fishing technologies targeting SPS in Lake Albert.* Using a mixed-methods approach (Creswell, 2014), data were collected in August 2020 through structured questionnaires, direct field observations, focus group discussions (FGDs), and key informant interviews (KIIs) (Morgan, 1996; Longhurst, 2003; Rindfleisch et al., 2008; Zohrabi, 2013; Gaizauskaite, 2012). While questionnaires, FGDs, and KIIs were used to capture stakeholder perceptions, attitudes, and knowledge regarding artificial light fishing technologies, direct observations provided additional empirical insights into actual fishing practices, gear use, compliance behaviour, and interactions among different user groups, thereby extending the analysis beyond stated perceptions.

In addition, the study characterized fishery users by documenting their roles within the fishery, fishing experience, gear ownership, target species, and patterns of participation in light-assisted fishing. This allowed the analysis to situate perceptions within the broader social and operational context of the fishery, recognizing fishers as heterogeneous actors whose behaviours and decisions influence exploitation outcomes. Data were collected at Ntoroko, Kaiso, and Dei landing sites, selected to represent the northern, central, and southern lake regions, respectively, and identified through prior NaFIRRI surveys as areas of high light-fishing activity (NELSAP, 2021a).

**Objective 2:** *Map the spatial-temporal distribution of SPS and light fishing effort in Lake Albert.*

Data sources included: Commercial catch records (2019–2022), Acoustic surveys, Spatial mapping of fishing effort, and Historical effort and catch data (2007–2022). The lake was zoned into northern, central, and southern regions (NaFIRRI, 2007; 2012; 2018; 2019; 2021), and monthly Catch Assessment Surveys (CASs) were conducted at selected landing sites during four lunar phases (new moon, first quarter, full moon, and third quarter) to capture the effect of lunar illumination. Spatial analyses were guided by Hamilton et al. (2022) to capture distribution across depth gradients and habitats.

**Objective 3:** *Determine life history traits of *E. bredoi* and *B. nurse*.* Experimental fishing was conducted at four lake sites (2 shallow, 2 deep). Fish were captured using solar and kerosene lights under varied intensities, with net settings standardized across trials. Biometric data were collected and analyzed to estimate maturity, fecundity, sex ratios, growth, and mortality following methods in King (1995), LVFO (2005, 2007), and Pinello et al. (2017).

**Objective 4:** *Evaluate the effects of light fishing technologies on target and non-target species.* This objective addressed concerns about net panel expansion and increased light intensities. It utilized both commercial and experimental data under controlled settings with variations in net panel length, light type, and intensity across shallow and deep habitats.

**Objective 5:** *Establish biological reference points (BRPs) for *E. bredoi* and *B. nurse*.* Catch, effort, weight, and length data from both experimental and commercial surveys were input into the FAO FISAT II software to estimate growth parameters and derive BRPs (Pauly & Gayanilo, 1997).

## CHAPTER FOUR

### EVALUATION OF STAKEHOLDER PERCEPTIONS OF ARTIFICIAL LIGHT FISHING TECHNOLOGIES TARGETING SMALL PELAGIC SPECIES IN LAKE ALBERT.

#### CONTEXT

This chapter investigates the socio-economic and governance complexities arising from the introduction and rapid expansion of light-based small pelagic species (SPS) fishing on Lake Albert. By synthesized stakeholder interviews and focus group discussions, the research explores the divergent perceptions between pelagic fishers and traditional demersal fishers regarding resource competition and ecological impact. The core problem identified is a growing crisis of social cohesion, fueled by the perception among traditional fishers that the highly efficient light-attraction technologies act as "vacuum cleaners" that indiscriminately harvest juvenile Nile perch and other high-value stocks. These perceived threats have escalated into overt spatial conflicts and gear sabotage, undermining existing local management structures.

The findings reveal that while pelagic fishers view light fishing as a vital socio-economic lifeline that compensates for the decline of large-bodied species, they also acknowledge the lack of standardized regulations as a driver of instability. The study highlights that the "nature and magnitude of conflicts" are often exacerbated by the absence of clear spatial zoning and the use of unregulated, deep-set nets that penetrate demersal nurseries.

To bridge these socio-political divides, the chapter argues for a management approach grounded in participatory governance and conflict transformation. By integrating stakeholder perceptions with the technical and biological evidence presented in later chapters, management can move toward a more inclusive and transparent framework. This approach not only addresses the immediate social tensions but also fosters a sense of collective ownership necessary for the successful implementation of the ecosystem-based management (EBM) strategies required to safeguard Lake Albert's multispecies future.

The detailed chapter is presented as a publication titled "Light-based small pelagic species fishing in Lake Albert: Divergent perceptions, conflicts, and implications for multispecies fishery management. *Journal of Great Lakes Research*, 102664. (10.1016/j.jglr.2025.102664)"



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## Light-based small pelagic species fishing in Lake Albert: Divergent perceptions, conflicts, and implications for multispecies fishery management

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### ABSTRACT

Introduced around the turn of the 21st century, light-based fishing targeting small pelagic species (SPS) like *Engraulicypris bredoi* and *Brycinus nase* (belonging to orders Cypriniformes and Characiformes, respectively, and known locally as muziri and rogoogi) has markedly transformed Lake Albert's artisanal fishery. SPS now constitute an estimated 60–70% of the lake's annual catch, signalling a shift from the previously dominant large-bodied demersal species that defined the fishery until the 1990s. While this expansion reflects growing significance of SPS in contemporary fisheries, it has generated divergent perceptions and conflicts among stakeholders. These tensions are exacerbated by the lack of empirical evidence on the ecosystem-wide effects of light-based fishing, particularly its impacts on stocks of large-bodied species. This study, conducted across three landing sites (Dei, Kaiso, and Ntoroko) spatially spread along the Lake Albert shoreline, employed qualitative methods, including structured questionnaires and interviews, to investigate stakeholder perceptions of light-based fishing. Fishers targeting large-bodied species reported concerns over increased bycatch, gear damage, habitat degradation, and spatial competition. In contrast, stakeholders in the SPS sector emphasized the socio-economic benefits of the light fishery, particularly employment and income opportunities for youth and women along the entire value chain, from fishing to processing and trade. The contrasting views underscore the complexity of managing a rapidly evolving multispecies fishery. The findings highlight the urgent need for ecosystem-based assessments of light-based fishing impacts to inform science-based management strategies that can promote the sustainable growth of the SPS fishery while fostering coexistence and equity among diverse fisher groups.

### 1. Introduction

Lake Albert, a transboundary African Great Lake shared between Uganda and the Democratic Republic of the Congo (DRC), supports a biologically diverse, multispecies fishery targeting both large-bodied and small-sized species (Mbabazi et al., 2012; Nakiyende et al., 2023a, 2023b, 2025; Wandera and Balirwa, 2010). This fishery is characterized by a wide range of gear types adapted to exploit the lake's ecological

heterogeneity (NaFIRRI, 2012; Nakiyende et al., 2023b), yet it faces multifaceted management challenges that threaten its long-term sustainability. The diversity of fishing gears used on Lake Albert (Table 1) reflects the fishery's multi-species nature (Mbabazi et al., 2012; 2019; NaFIRRI, 2012; Nakiyende et al., 2023a, 2023b).

Current national fishing regulations, the Uganda Fish (Fishing) Rules (Government of Uganda, 2010), permit gillnets with 4-inch (10 cm) minimum mesh size and longline hooks of size number nine and below,

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for the harvest of large-bodied species such as *Lates niloticus* (Nile perch), *Oreochromis niloticus* (Nile tilapia), *Bagnus bajad* (Black Nile catfish), and *Labeobarbus bynni* (Nile barb). For small pelagic species (SPS), such as the cypriniform *Engraulicypris bredoi* (known locally as muziri) and characiform *Brycinus nurse* (nurse tetra or ragoogi locally), small seine (lampara) nets of 8 mm mesh size are permitted.

Despite these regulations, a wide range of illegal gears are in use (Table 1). Gillnets with mesh sizes below the legal 4-inch threshold and longlines below the legal limits (Government of Uganda, 2010) are commonly used for the capture of juveniles and undersized individuals of large-bodied species (e.g., *Lates niloticus* and characiforms such as *Alestes baremose* (pebbly fish) and *Hydrocynus forskahlii* (elongate tigerfish)) and SPS (e.g., *B. nurse*). Additionally, active (illegal) gears such as beach seines, boat seines, and cast nets are also used across diverse habitats (inshore and offshore), often resulting in non-selective catches. Basket traps, another illegal method, are frequently used to harvest species like *Clarias gariepinus* (North African catfish), *Malapterurus electricus* (electric catfish), *Synodontis* spp. (squeakers, catfish family Mochokidae), and *Mormyrus* spp. (elephant-smout fishes). The observed prevalence of illegal fishing gears despite the existence of clear fishing regulations suggest both non-compliance and weak enforcement, possibly due to complexities involved in enforcing such regulations in a multispecies fishery like the one in Lake Albert.

Light fishing, a method that uses night-time illumination to attract fish, particularly shoaling SPS, is the primary technique used to harvest *E. bredoi* and *B. nurse* in Lake Albert (Namboozo, 2008; Mbabazi et al., 2012, 2019; NaFIRRI, 2012; Nakiyende et al., 2023a, 2023b). The technique is widely practiced globally and has a historical lineage (Nguyen and Winger, 2019; Solomon and Ahmed, 2016). Its efficacy in capturing SPS is well-documented (Solomon and Ahmed, 2016; Yami, 1976). The technology has evolved from simple tools such as torches to floating oil, kerosene, and gas lanterns, and it now includes high-intensity lighting systems such as incandescent, fluorescent, LED, and solar-powered lamps (Mills et al., 2014; Solomon and Ahmed, 2016; Yami, 1976).

In the African Great Lakes, light-based fishing was first introduced in Lakes Tanganyika and Malawi, where it targeted SPS such as *Stolothrissa tanganica* (Lake Tanganyika sprat), *Limnothrissa miodon* (Lake Tanganyika sardine), and *Engraulicypris sardella* (Lake Malawi "sardine") (Kolding et al., 2019). In Uganda, the technology was first adopted on Lake Victoria in the early 1970s for harvesting *Rastrineobola argentea* (silver cyprinid) (Wandera, 1993), and it was later extended to Lake Kyoga in the 1990s and Lake Nabugabo around 2009 (Groves et al., 2022). Lake Albert embraced light-based fishing in the early 2000s (Namboozo, 2008; NaFIRRI, 2012), following these earlier implementations. The method employs illuminated lampara nets as the

primary gear to target the two key SPS *E. bredoi* and *B. nurse* (Mbabazi et al., 2012, 2019; NaFIRRI, 2012; Nakiyende et al., 2023a, 2023b).

Light-based fishing practices remain a major source of contention among different fishing clusters, fuelling conflict between those for and those opposed to its use (NaFIRRI, 2012; Nakiyende et al., 2023a, 2023b; Nile Post, 2024; Uganda Radio Network, 2006). These conflicts have been documented in recent media reports and institutional studies highlighting tensions at various landing sites, over access, gear configurations, and ecological impacts (Harvest Money, 2024b; NaFIRRI, 2012; The Cooperator News, 2024). The primary driver of this conflict is the unregulated nature of the light-based SPS fishery, characterized by a perceived excessive use of small seine net panels and diverse light sources (such as solar bulbs and kerosene lanterns). The night-time operation of these gears is perceived to result in high bycatch levels, particularly of juvenile Nile perch, raising concerns about potential threats to fish biodiversity and the long-term sustainability of the fishery (Solomon and Ahmed, 2016).

Contributing to this increase in effort, the expansion of the SPS fishery has seen fishers transition from the original 2–3 kerosene lamps and 4–6 net panels per boat to the use of solar lamps and up to 20 net panels per boat (Mbabazi et al., 2012; NaFIRRI, 2012; Nakiyende et al., 2023a). The scarcity of scientific data, particularly concerning gear selectivity and the impacts of light fishing techniques (including net panelling) on the SPS fishery and other stocks, hinders the development of effective management policies and strategies. This exposes both the SPS fishery and non-target (bycatch) species to overexploitation and potential collapse, and it continues to escalate conflict among fishing communities.

The conflict has led stakeholders aligned with large-bodied species, particularly Nile perch fishers, to lobby the Ugandan government to halt SPS fishing, citing concerns over declining catches and juvenile bycatch (Nile Post, 2024; Uganda Radio Network, 2006). This advocacy culminated in a controversial ministerial directive from the minister of state for fisheries resources, suspending the use of light-based gears (small seine nets and solar lights) via media pronouncements (Harvest Money, 2024a; Daily Monitor, 2024b; Uganda Radio Network, 2006), despite the absence of a clearly articulated legal or scientific basis.

However, enforcement of this directive by the Fisheries Protection Unit (FPU), a specialised arm of the Uganda People's Defence Force (UPDF) established in 2017 to support the Directorate of Fisheries Resources (DiFR) in fisheries control and surveillance, has faced strong resistance from SPS fishers and value chain actors (Africa-Press, 2024; Harvest Money, 2024b; Monitor, 2024; The Cooperator News, 2024; Uganda Times, 2024). Stakeholders have questioned both the fairness and effectiveness of the enforcement, citing continued use of similar technologies, particularly solar lights and small seines, in neighbouring

Table 1

Characteristics of fishing gears and targeted species in Lake Albert, including gear legality and common catch patterns. Data Source: NaFIRRI (2012), Mbabazi et al. (2012), NELSAP (2021b), Nakiyende et al. (2023). (\*) denotes gear legality based on classification under the Fish (Fishing) Rules (Government of Uganda, 2010), (\*\*) denotes species commonly retained in 2 & 3-inch mesh sizes (5.1 & 7.6 cm), and (\*\*\*) denotes species commonly retained in meshes below 2 in. (< 5.1 cm).

Gear Type	Legality*	Mode of Operation	Primary Target Species	Primary Fishing ground	Fishing Period
Gillnets ≤ 4 in. (10 cm)	Illegal	Active, passive	<i>Alestes baremose</i> **, <i>Hydrocynus forskahlii</i> **, <i>Lates niloticus</i> , <i>Oreochromis</i> spp., <i>Brycinus nurse</i> ***, <i>Synodontis</i> spp., <i>Mormyrus</i> spp.	Shallow inshore	Day and night
Gillnets ≥ 4 in. (10 cm)	Legal	Active, passive, drifting	<i>Lates niloticus</i> , <i>Oreochromis</i> spp., <i>Ditichodus niloticus</i> , <i>Bagnus bajad</i>	Both shallow inshore and deep offshore	Night
Longline hooks (Baited)	Legal	Passive	<i>Lates niloticus</i> , <i>Oreochromis</i> spp., <i>Bagnus bajad</i> , <i>Clarias gariepinus</i> , <i>Malapterurus electricus</i>	Deep offshore	Night
Beach seines	Illegal	Active	<i>Lates niloticus</i> and all other species retained	Shallow inshore	Day
Boat seines	Illegal	Active	<i>Lates niloticus</i> , <i>Bagnus bajad</i> , <i>Alestes baremose</i> , <i>Hydrocynus forskahlii</i>	Deep offshore	Day
Cast nets	Illegal	Active	<i>Oreochromis</i> spp.	Shallow inshore	Day and night
Illuminated small seines	Legal	Active	<i>Engraulicypris bredoi</i> , <i>Brycinus nurse</i>	Both shallow inshore and deep offshore	Night
Basket Traps	Illegal	Baited, Passive	<i>Clarias gariepinus</i> , <i>Malapterurus electricus</i> , <i>Synodontis</i> spp., <i>Mormyrus</i> spp.	Shallow inshore	Day and night

countries such as Kenya and Tanzania (LVPO, 2020; 2022). These concerns are further complicated by the inadequate regulation of the light-based fishery, which targets primarily SPS such *R. argentea*, *E. breddoi*, and *B. nurse* (NELSAP, 2021b; LVPO, 2022). Uganda's existing regulations, Fish (Fishing) Rules (Government of Uganda, 2010), specify legal mesh sizes for lampara nets of 8 mm for Lake Albert and 10 mm for Lakes Victoria and Kyoga. However, the regulations are silent on other crucial aspects of the fishery, such as the allowable number of net panels (net depth) as specified for gillnets, and the type or intensity of light used, key concerns raised by stakeholders opposed to light-based fishing practices.

The regional inconsistency, combined with the lack of scientific evidence specific to the impacts of light usage and net panelling, has triggered a series of stakeholder consultations, including technical meetings, policy dialogue, and roundtables. These have involved fisheries managers, the FPU, researchers, and academics; regional management bodies such as the Lake Victoria Fisheries Organisation (LVPO) and the Lake Edward and Albert Fisheries and Aquaculture Organisation (LEFAO); and representatives from fisher associations, including the Association of Fishers and Lake Users in Uganda (AFALU). A key outcome from these engagements was a consensus on the need for evidence-based research to guide the formulation of harmonised and context-appropriate SPS management regulations across Uganda's lakes.

Emerging trends from several African Great Lakes, such as Victoria, Malawi and Tanganyika, indicate a growing dominance of SPS in artisanal catches, which has altered catch composition and reduced proportional contribution of large-bodied species in overall landings (Groves et al., 2022; Kolding et al., 2019; LVPO, 2020; NaFIRRI, 2012; Nakiyende et al., 2023a, 2023b). Although this shift does not necessarily signify a decline in absolute abundance of large-bodied species (Kolding et al., 2019), it has heightened stakeholder perceptions that light-based fishing may be displacing traditional high-value species. These perceptions, in the absence of robust empirical evidence establishing the direct link, continue to fuel controversy around light-based fishing practices. The contention is further amplified by unresolved ecological and socio-economic concerns, particularly regarding net stacking, light type and intensity, and juvenile bycatch. While scientific literature explicitly linking light-based fishing to user conflicts across other African Great Lakes remains limited, the tensions observed on Lake Albert underscore the potential for similar disputes to emerge in other lakes, such as Victoria, Kivu, Tanganyika, and Malawi/Niassa/Nyasa, where light-based fishing technologies are widely used for harvesting SPS (LVPO, 2020, 2022; Mangeni-Gande et al., 2019; Mgana et al., 2019).

Despite the controversies surrounding light fishing techniques in Lake Albert, SPS—especially *E. breddoi* and *B. nurse*—have become increasingly important in sustaining livelihoods around Lake Albert (Namboozo, 2008; Mbabazi et al., 2012; Nakiyende et al., 2023a, 2023b). Evidence from these studies show a marked increase in light-based fishing effort since the early 2000s, accompanied by a significant shift in catch composition, from large-bodied species to SPS dominance, largely attributed to the adoption of light fishing technologies. Currently, the light-based fishery in Lake Albert contributes approximately 70 % of the lake's total annual catch, supports about 60 % of local fisheries-related employment, and involves nearly 40 % of the active fishing boats (Mbabazi et al., 2019; Nakiyende et al., 2023a). Similar trends of increasing SPS contribution to total landings have been documented in some African Great Lakes, particularly Lakes Victoria, Malawi, and Tanganyika (Kolding et al., 2019). In many of these lakes, SPS now account for 50–70 % of total annual catch landings, surpassing those of large-bodied species (Kolding et al., 2019). This transition aligns with patterns observed in multispecies fisheries, where rising fishing pressure increases exploitation of smaller-bodied species, consistent with the concept of balanced harvesting, which promotes moderate fishing mortality across all size classes (Garcia et al., 2016; Kolding et al., 2016).

Beyond their economic role, SPS also provide an affordable and highly nutritious source of animal protein for rural communities (Aura et al., 2022; Clarke et al., 2022; Efitre et al., 2023; FAO, 2023; Isaacs, 2016; Kolding et al., 2019). Their ease of processing, especially sun-drying, extends shelf life and improves local distribution without the need for packaging or refrigeration (Ikape and Cheikyula, 2017; Masette, 2013; Masette and Khakara, 2012). While direct human consumption of SPS in urban Uganda remains limited due to perceived hygiene concerns, their growing use in animal feed production further enhances their utility (Afreen and Ucak, 2020; FAO, 2023; Masette and Khakara, 2012; Tacon and Metian, 2009).

Recognizing the critical role of stakeholder perceptions in shaping fisheries, recent literature emphasizes the importance of participatory approaches in the development and implementation of inclusive policies and management initiatives (van Densen and McCay, 2007). However, effective integration of stakeholder insights into policy frameworks requires careful evaluation, as perceptions often reflect divergent understandings of fisheries systems, shaped by differing priorities and knowledge bases across groups, such as scientists, fishers, managers, and policymakers (Verweij and van Densen, 2010).

This study, therefore, examined and documented the varied stakeholder perspectives regarding the use of light attraction fishing technologies for harvesting SPS in Lake Albert. Specifically, it aimed to understand:

- Stakeholder perceptions of light attraction fishing techniques, including solar lamps, kerosene lamps, and vertical joining of nets (net panelling), in terms of their effects on the catch rates of both target species (SPS) and non-target species (bycatch).
- The key sources of conflict between different fishing groups, associated with the SPS light fishing methods.
- The main challenges affecting the SPS light-based fishery.
- The stakeholder-proposed management measures and their perceived effectiveness in mitigating conflict and promoting the ecological, economic, and social sustainability of this multispecies fishery.

This study was focused on Lake Albert and provides a foundational basis for further scientific investigations, particularly those exploring ecological dynamics and gear-use conflicts. Its findings are directly relevant to the development of evidence-based fisheries policies and management strategies that promote conflict resolution and the sustainable coexistence of diverse fishing practices within the Lake Albert multispecies fishery.

## 2. Methods

### 2.1. Study area and scope

The study was conducted on the Uganda side of Lake Albert, where light fishing techniques targeting SPS are more prevalent (NELSAP, 2021b, 2021a; Nakiyende et al., 2023a, 2023b). Cross-sectional (single point) data collection occurred at each study site in August 2020, prior to the FPU's enforcement of the ministerial directive to suspend SPS fishing (particularly with solar lights), ensuring the inclusion of all targeted respondent categories. Three landing sites were selected for the study: Ntoroko (Southern), Kaiso (Central), and Dei (Northern) (Fig. 1). These sites were chosen due to their active fisheries for both SPS and large species, with over 200 fishing boats operating at each site. The stakeholder respondents comprised four broad categories: fishers, fish traders/processors, beach management leaders, and district local government fisheries managers (District Fisheries Officers) (Table 2).

To facilitate comprehensive data collection, stakeholder respondents for Focus Group Discussions (FGDs), excluding beach management leaders and District Fisheries Officers, were categorized into two distinct groups based on their involvement in either the large-bodied species

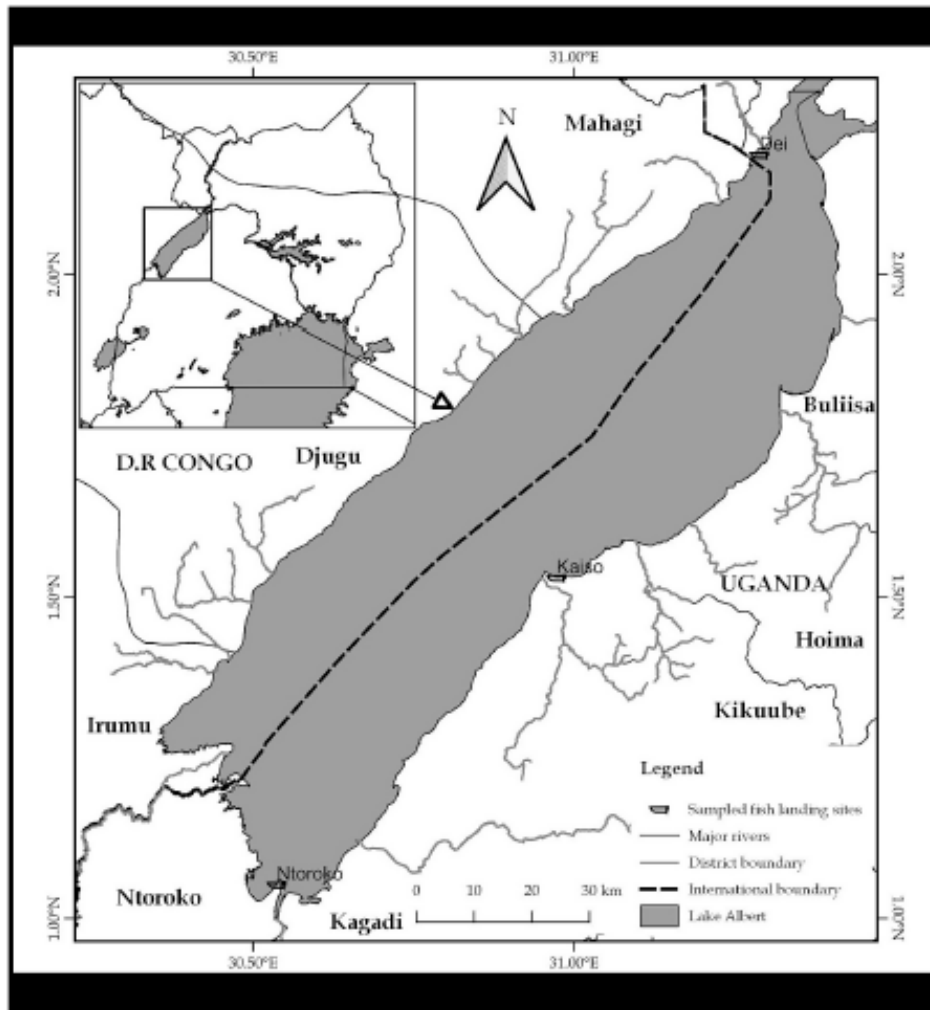


Fig. 1. Map of the study area. Inset shows the location of Lake Albert in the map of Uganda.

Table 2  
Perception study on Lake Albert: Respondents, data collection tools and sample size.

Category of respondent	Tool used	Sample size
Fishers targeting SPS and large species	Semi-structured questionnaire	Total of 82 respondents (14 respondents per fisher group at Kaiso and Dei landing sites and 13 respondents per fisher group at Ntoroko landing site)
Fish processors and fish traders at landing site	Focused Group Discussion (FGD) checklist	Three FGD groups (comprising 10–12 members) administered at each study landing site
District fisheries extension staff	Key Informant Interviews (KII)	One interviewee per district
Landing site leaders	KII	One interviewee per landing site

value chain (fishers, traders, and processors, dominated by Nile perch) or the SPS value chain (dominated by *E. brederi* and *B. muriei*). Fish processors and traders for both species groups were included because they are integral to the fishing community, directly receiving fish from fishers, and some serve on beach management committees. Similarly,

beach management leaders and fisheries managers possess valuable knowledge of fishing operations at the study sites due to their respective leadership and management roles.

2.2. Data collection method

The study adopted a mixed-methods approach (Creswell, 2014), combining both qualitative and quantitative data collection techniques. Semi-structured questionnaires (Electronic Supplementary Materials (ESM) Appendix S1) were used to gather quantitative data, while FGDs and Key Informant Interviews (KIIs) provided qualitative data (Gaisauskaite, 2012).

2.2.1. Structured qualitative data collection

Structured face-to-face interviews were conducted using a questionnaire (ESM Appendix S1) administered separately to fishers (boat captains) targeting SPS and large species (LS) at the three study landing sites (Table 2). Interviews were carried out during peak activity periods: morning (06:00–11:00) and evening (16:00–18:00) to ensure interaction with fishers returning from or preparing for fishing trips. A total of 82 fishers, primarily boat captains (41 targeting SPS and 41 targeting LS) were interviewed, providing balanced representation of the two fishing

groups (Table 2).

A stratified random sampling approach was employed at the boat level, to ensure a representative sample. Using data from the 2020 Frame Survey (NaFIRRI, 2021) and guided by landing site chairpersons familiar with local operations, fishing boats were categorized into two strata based on target species: (i) SPS boats using light attraction methods and (ii) LS boats using gillnets and hooks. Gillnet and longline boats were selected based on their legality, as these gear types are permitted for use on Lake Albert under the Fish (Fishing) Rules (Government of Uganda, 2010). Within each stratum, active fishing units were listed and “sample boats” were randomly selected using R software (R Core Team, 2024). Boat captains or their designated representatives were interviewed using the structured questionnaire (Table 2).

### 2.2.2. Unstructured qualitative data collection

In addition to the structured interviews, FGDs (Gaisaunakaite, 2012) were held with three stakeholder categories: fishers targeting SPS, fishers targeting LS, and fish processors/traders. Participants were nominated by landing site leaders based on their knowledge of landing site dynamics, ensuring no overlap with individuals previously interviewed to avoid bias. Each FGD comprised 10–12 participants (Table 2), providing a platform for open discussion and the sharing of divergent perspectives.

The FGDs explored perceived drivers of conflict between fishing groups and gathered local stakeholder insights on inclusive and feasible management options. Particular attention was given to contentions surrounding the incidental capture of juveniles of high-value large-bodied species such as Nile perch, *H. forskahlii*, and *A. baremose* by SPS gears. These discussions enriched the study by capturing local knowledge and practical ideas for conflict-sensitive fisheries management strategies. Additionally, KIs were conducted with District Local Government Fisheries Officers and landing site (beach) leaders to complement fisher perspectives and provide broader institutional insights into emerging conflict issues and perceptions on the use of light-based fishing methods.

### 2.3. Data processing and analysis

Descriptive statistics were used to summarize respondents' characteristics and to provide an overview of their perceptions. Qualitative data from the KIs and FGDs were organized into thematic matrices. Analysis of this qualitative data focused on identifying recurring issues and perspectives, which were then synthesized and reported under emerging themes. These qualitative insights complemented the interview-based findings and enriched the understanding of stakeholders' perceptions regarding the SPS light-based fishery on Lake Albert.

To examine how seasonal variations and light fishing technology influenced fishing success, a two-way ANOVA was conducted to test for significant differences in mean catch rates (catch-per-unit-effort, in kg/boat/day) of *E. brederi* and *B. nurse* across two factors: seasons (high vs. low catch periods) and light sources (solar-powered vs. kerosene-powered lights). The catch rate data for this analysis were based on fisher-reported estimates from semi-structured interviews. While answering question 13 (on quantity of catch landed per day) (ESM Appendix S1), respondents across the study sites consistently mentioned that catches differed between two main fishing seasons: high-catch (peak) and low-catch periods. This information was followed up during interviews, and respondents were requested to estimate typical daily catch quantities for each season across the different light sources and indicate the corresponding months. These estimates were recorded and later organized for comparative analysis. This analysis addressed the study objective of understanding fishers' perception of factors shaping SPS dynamics on Lake Albert.

### 2.4. Ethical considerations

Ethical clearance for this study was granted by the Uganda National Council of Science and Technology (UNGST) under the “NUTRIFISH Project.” Prior to conducting interviews, informed consent was obtained from willing participants. This involved transparently communicating the survey's purpose, the intended use of their data, potential benefits, and assurances of confidentiality and anonymity. Measures were implemented to protect respondent privacy, including refraining from exposing names and contact details, and utilizing secure storage and encryption methods to prevent unauthorized access to the data.

## 3. Results

### 3.1. Perceived causes of fishing conflict on Lake Albert

All study respondents (100%), including those from FGDs and KIs, unequivocally acknowledged the existence of fishing conflict in Lake Albert. These conflicts primarily manifest between fishers targeting SPS using light attraction techniques and those targeting LS using traditional gillnets and long-line hooks. The frequently cited cause of conflict by both groups was the perceived high bycatch of juveniles of commercially important LS, particularly Nile perch, by SPS-targeting gears (LS respondents: 90.2%; SPS respondents: 68.3%). In addition, the increasing use of solar lights was identified as a major driver of tension (LS respondents: 75.6%; SPS respondents: 43.9%) (Table 3).

Other contributing factors included overlap and competition for fishing grounds, perceived excessive effort in the SPS fishery (characterized by a surge in fishing boats, an increase in the number of fishing lights from 2 to 3 kerosene lanterns to many as 21 solar bulbs per boat, and expansion of net panelling from 4 to 6 to currently 18–20 panels), often happening in the absence of clear regulatory limits or scientific guidance. Additional sources of conflict included theft or destruction of fishing gears and catch, perceived damage to lake bottom and associated communities, especially by small seine nets during their active operation, and the perceived disturbance or “scaring away/gear avoidance” of large-bodied fish species (Table 3). Specifically, solar lights were perceived to be excessively bright, increasing the visibility of LS fishing gears, particularly gillnets. This enhanced visibility was believed to trigger avoidance behaviour in target LS, thereby resulting in reduced catch rates for fishers using these traditional gears. It is also noteworthy

Table 3  
Perceived causes of fishing conflict among fishers on Lake Albert, Uganda. Data from small pelagic species (SPS) and large species (LS) fishers' respondents, n = 82.

Source of conflict	Large species (n = 41)		Small pelagic species (n = 41)	
	No. of respondents	% Response	No of respondents	% Response
Scare of large fish species	11	26.8		
Competition for space at fishing ground	25	60.9	17	41.5
Destruction of critical habitats	9	22.0		
High bycatch of large species	37	90.2	28	68.3
Theft of fishing gear and catch	18	43.9	13	31.7
Excessive SPS fishing effort	26	63.4		
Use of solar light	31	75.6	18	43.9

that the majority of respondents were male (89 %) (ESM Fig. S1), reflecting the male-dominated nature of the fisheries value chain on Lake Albert.

3.2. Perceptions on light types used to harvest SPS and associated impacts

In the SPS fishery, solar bulbs and kerosene lanterns were the primary sources of light used for fish attraction (Table 4). Among SPS-targeting respondents, solar lights were overwhelmingly preferred, with 90.2 % indicating them as their choice. This strong preference was attributed to their perceived cost-effectiveness, enhanced catch performance, user-friendliness, market availability, and relatively lower environmental impacts compared to kerosene lanterns (Table 4). In contrast, SPS-targeting fishers who reported using kerosene lanterns indicated that their decision was influenced by compliance with a Ministerial directive suspending the use of solar lights, enforced by the FPU, as to avoid arrest and prosecution.

Although LS fishers do not directly use light attraction in their operations, the majority (78 %, n = 41) expressed a preference for kerosene lanterns in the SPS fishery over solar lamps. This preference stemmed from their perception that kerosene lanterns emit lower-intensity lights, which results in reduced bycatch of juvenile LS, particularly Nile perch. They believed this reduction in juvenile bycatch would minimize adverse effects on the sustainability and future availability of adult LS stocks.

FGD participants widely perceived solar-powered lamps as more advantageous compared to traditional kerosene lanterns. They cited lower maintenance costs, longer operational lifespan, greater reliability (less prone to extinguishing), and better environmental performance, particularly due to the absence of fuel spillage and greenhouse gas emissions. One FGD participant noted:

*“After purchasing the solar, it can take four to six months when it’s still working efficiently without repairs, yet lanterns require daily expensive maintenance and repairs.”*

KIs including Fisheries Officers and landing site leaders echoed these views. They advocated for a gradual shift from kerosene lanterns to solar-powered lamps, citing their cost-effectiveness, environmental benefits, and operational convenience.

Both FGD participants and most KIs associated lanterns with multiple risks and operational challenges. These included boat accidents caused by bursting flames (sometimes resulting in burns or drowning), fuel spillage on water and fish catch, the need for frequent pumping to maintain flame intensity, vulnerability to wind, and high maintenance costs. As one FGD participant explained:

*“Lanterns require attention throughout the fishing activities through pumping to maintain the flame, so the fishers don’t have time to relax while on the lake, while the solar lights are easy to use.”*

These findings reflect a broad stakeholder consensus favouring solar lighting, largely due to its safety, efficiency, and sustainability advantages.

3.3. Perceived bycatch composition in light-based SPS fisheries

The proportion of bycatch was assessed based on fishers’ self-reported estimates of its perceived contribution to the total catch. Two fish species, *E. bredoii* and *E. nurse*, were consistently identified as the dominant catch of the SPS light fishery on Lake Albert (Fig. 2). The perceived incidence of bycatch did not vary significantly ( $p < 0.05$ ) between light sources, accounting for 8.1 % and 8.5 % (by weight) of the total SPS catch per boat per day for solar and kerosene lamps, respectively (Fig. 2). Across both light types, the most frequently reported bycatch species included juvenile Nile perch, *Alestes* spp., *Hydrocynus* spp., and *Oreochromis* spp. (Fig. 2). It is important to acknowledge that these self-reported estimates may differ from empirically measured data,

Table 4 Comparative advantages of fishing light types (solar bulbs and kerosene lanterns) utilized for harvesting small pelagic fish species (SPS) on the Ugandan side of Lake Albert.

Attribute	Solar bulbs	Kerosene lanterns
Catch per unit effort (catch rates)	Associated with high catch rates	Associated with lower catch rates
Cost, availability, and accessibility of components and accessories	Main components and accessories are cheap and readily available on the market	Components and accessories are scarce and expensive
Daily fuel requirements	Charging is by solar energy, making its use cheap and more profitable, except during rainy days.	Require daily refilling of paraffin, making it expensive to run and less profitable
Potential for pollution of the lake environment	Lesser risk of environmental pollution. Charging is done by clean solar energy on landing, but the disposal of old batteries could be a potential hazard	Prone to fuel leakage, spillage, and seepage into the lake, especially during bad weather days
Energy cleanliness and pollution	Solar is a clean source of energy with no risk of environmental pollution	Associated with greenhouse gas emission into the environment, contributing to destruction of ozone layer
Potential for catch contamination	No risk of catch contamination	Associated with risks of contamination of the catch through leakage of paraffin
Operating costs	Low costs associated with its operation	High costs of maintenance due to regular replacement of broken parts and high cost of fuel
Effects of bad weather such as strong winds and waves on the light technology	Can withstand bad weather conditions such as rain, strong winds, and waves. Solar bulbs can continue lighting even after flipping over	Severely affected during bad weather, easily blown off, can flip over and spill fuel into the lake. Often lost in bad weather, increasing accident risks
Risk of accidents	No accident risks associated with solar bulbs	High risk of accidents such as fire and explosion due to contact between outboard engine petrol and heat generated from the kerosene lamps
Ease of use and operation	User-friendly operation with simple on/off switches and charging during the day while fishermen rest	More laborious to use, requiring thorough cleaning, time-consuming lighting and extinguishing processes, and constant pumping to maintain sufficient pressure
Shelf life and longevity	Solar batteries and panels have a long lifespan when well maintained. Solar bulbs can last for over six months	Some accessories are single-use, glasses are prone to breakage, requiring constant repairs and replacement
Health hazards and environmental risks	No documented health risks associated with solar bulbs. However, disposal of batteries and bulbs can be challenging	Emit carbon monoxide and fine soot particles, posing health risks. Consumption of contaminated fish also poses health risks
Investment, operation, and maintenance costs	Higher initial investment costs with higher return on investment and shorter payback period	Lower initial investment costs but higher maintenance costs and fuel expenses, resulting in a higher total life cycle cost and lower return on investment

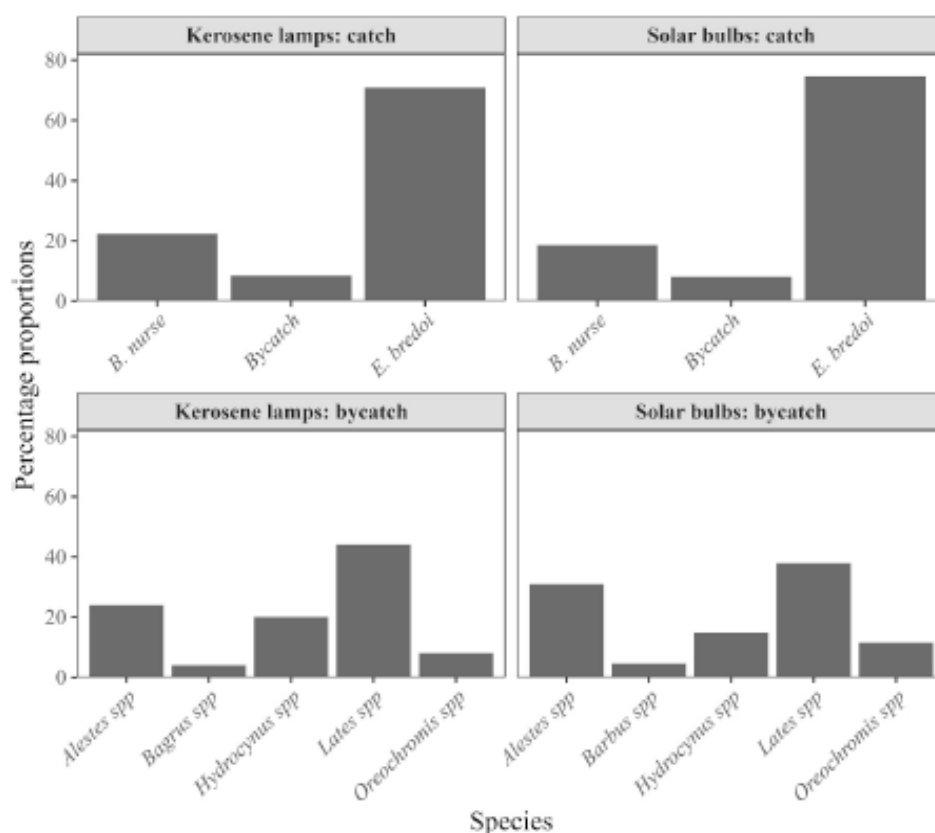


Fig. 2. Perceived composition of total catch by light type (upper panels) and bycatch species composition by light type (lower panels), expressed as percentage proportion in the light-based small pelagic species (SPS) fishery on Lake Albert.

due to factors such as respondent bias, variations in the interpretation of what constitutes “bycatch,” or economic incentives. These limitations could highlight a need for empirical studies to validate these observations by comprehensively evaluating bycatch composition, to determine sustainable limits, and develop appropriate mitigation strategies.

FGD participants expressed mixed views on bycatch. On one hand, bycatch was seen as economically beneficial, contributing to total landings and increasing income from the light-based SPS fishing. On the other hand, it was viewed as a threat to the sustainability of LS stocks. One participant remarked:

“There is usually a lot of bycatches, which enhances our catches and earnings from the *musiri* and *ragoge* fishery.”

Conversely, another explained:

“It is because of excessive juvenile bycatch of the large-bodied species caught in small seines and solar bulbs which has caused the decline of all large-bodied species stocks.”

KII respondents, including fisheries officers, expressed similar concerns regarding sustainability, particularly the frequent presence of juvenile Nile perch in solar light catches. These observations underscore a clear divergence in stakeholder perceptions: while SPS fishers emphasized the economic gains, fisheries managers and LS fishers highlighted the potential long-term risks to stock sustainability and ecosystem stability.

### 3.4. Fishing grounds (habitats) for *Engraulicypris bredoi* and *Brycinus nurse*

Respondents identified two main habitats for SPS fishing: shallow inshore waters ( $\leq 20$  m, deep), including river mouths, and deeper open waters ( $> 20$  m, deep) (Table 5). The majority (80 %) of surveyed fishers operating in deeper offshore areas (20–40 m, deep) reported higher SPS abundance and catch rates. These fishers also noted their compliance with the 2-km buffer zone regulation (Government of Uganda, 2010), intended to safeguard sensitive inshore fish habitats (Wandera and

Table 5  
Perceptions of factors influencing choice of fishing grounds for *E. bredoi* and *B. nurse* on Lake Albert, Uganda. Data from SPS fisher respondents,  $n = 41$ .

Attribute	Inshore waters (< 20 m)	Deep open waters ( $\geq 20$ m)
Preferred choice of fishing ground	(22.6 %)	(77.4 %)
Factors influencing the choice of fishing habitat		
Security and safety at fishing ground	(7.1 %)	
Number of seine net panels required at fishing ground	(2.4 %)	
Investment and operational costs at fishing ground	(2.4 %)	
Large fishing area and low competition		(3.6 %)
Avoidance and protection of fish breeding areas		(27.4 %)
Better catch rates of <i>E. bredoi</i> and <i>B. nurse</i>	(6 %)	(17.8 %)
High abundance of <i>E. bredoi</i> and <i>B. nurse</i>	(4.8 %)	(28.6 %)

Balirwa, 2010). Conversely, respondents who preferred shallow inshore areas cited security and safety concerns in the deeper waters bordering the DRC, alongside lower operational and investment costs. Fishing in shallow areas typically required fewer net panels and less fuel, making it a more accessible and affordable option for small-scale operators.

### 3.5. Vertical joining of small seine net panels in light-based fisheries

On Lake Albert, both *B. nurse* and *E. bredoi* were harvested using surrounding lampara nets. Each boat commonly deploys between 6 and 18 nets, joined vertically, a practice locally referred to as gorofa (Fig. 3a). The number of net panels used was influenced by multiple factors: target fishing depth (51.3 % of respondents), anticipated catch (30.7 %), regulatory compliance (11.5 %), and financial capital (2.6 %) (Fig. 3b). Fishers operating in deep-water fishing grounds generally used more net panels to increase their catch rates, whereas those with limited capital opted for fewer panels in the shallow inshore waters. Notably, fishers using six panels reported doing so to comply with FPU's guidelines, as a precautionary measure aimed at regulating light fishing effort in the light-based fishery on Lake Albert.

### 3.6. Fishing crew, active fishing days, and factors influencing light-based fishing activity

Each light fishing boat targeting *E. bredoi* and *B. nurse* typically operated with a crew of 3–4 individuals per trip. Although light fishing was conducted year-round, the majority of respondents (61.9 %) reported fishing actively for about 15–21 days in each month, which is approximately 3 weeks per month (Fig. 4a). Fishing activity was influenced primarily by lunar phase and weather conditions. Most fishers (71.4 %) identified moonless (dark nights) as the most favourable periods for light fishing, while 11 % cited calm weather as another important factor (Fig. 4b). Adverse weather and full moon nights were reported to reduce fishing activity, due to decreased catchability and operational difficulties.

### 3.7. Variation in catch rates of *Engraulicypris bredoi* and *Brycinus nurse* by season and light source

The reported catch rates (catch-per-unit-effort in kg/boat/day) of both species did not differ significantly ( $p > 0.05$ ) between light sources (*E. bredoi*:  $t = 0.62$ ,  $df = 68.09$  and *B. nurse*:  $t = 0.22$ ,  $df = 131.03$ ). Nonetheless, *E. bredoi* consistently exhibited higher catch rates than

*B. nurse* (Fig. 5).

Fishers identified two distinct SPS production seasons in Lake Albert: high-catch (April to June and September to November) and low-catch (December to March and July to August) (Fig. 5). Catch rates varied significantly ( $p < 0.05$ ) between these seasons for both *E. bredoi* ( $t = 7.988$ ,  $df = 89.578$ ) and *B. nurse* ( $t = 3.4852$ ,  $df = 70.585$ ).

During high-catch periods, *B. nurse* catch-per-unit-effort ( $\pm$  standard error) averaged  $192.9 \pm 56.2$  kg/boat/day in solar lights and  $165.7 \pm 28.8$  kg/boat/day using kerosene lights. These declined to  $36.8 \pm 3.9$  kg/boat/day and  $55.1 \pm 10.9$  kg/boat/day, respectively, during low-catch seasons (Fig. 5). For *E. bredoi*, catch rates averaged  $466.41 \pm 52.9$  kg/boat/day (solar lights) and  $523.5 \pm 89.4$  kg/boat/day (kerosene lights) in the high-catch season, falling to  $88.1 \pm 13.1$  kg/boat/day and  $102.0 \pm 26.1$  kg/boat/day, respectively, during low-catch periods (Fig. 5).

The interaction between light source and season was not significant for either species (*E. bredoi*:  $F_{(1, 149)} = 0.329$ ,  $p > 0.05$ ; *B. nurse*:  $F_{(1, 131)} = 0.2164$ ,  $p > 0.05$ ).

### 3.8. Drivers of fishing effort shift from LS to SPS fisheries

Several factors were reported to influence the transition from traditional LS fishing methods (e.g., gillnets and hooks) to light-based SPS fishing (Table 6). The most cited driver was the perceived higher catch rates of light-based SPS gears, reported by 90.2 % of respondents (36 LS vs. 38 SPS fishers). Declining catch rates in traditional gears was cited by 78.0 % of respondents (30 LS and 34 SPS fishers), while 68.3 % (26 LS and 30 SPS fishers) identified high operational cost of traditional gears as a key factor, suggesting that economic considerations strongly influence gear choices. Gear theft, damage, or loss emerged as a key concern for 65.9 % (54 out of 82 respondents), particularly among SPS fishers (36 SPS vs. 18 LS respondents). Within this, 43.9 % (36 out of 82 respondents: 28 SPS vs. 8 LS) specifically mentioned frequent gear losses as a major factor.

Juvenile bycatch of large-bodied species within SPS catches, a key point of contention between fishing clusters, was reported by only 58.5 % of respondents (48 out of 82: 32 LS and 16 SPS). Heightened fisheries enforcement against illegal gear use also influenced the shift, reported by 51.2 % (42 out of 82; 16 LS and 26 SPS fishers). A minority of respondents (24.4 % or 20 out of 82; 12 SPS and 8 LS fishers) also cited the opportunity to rest, particularly during the full moon phase when light-based fishing is typically paused due to reduced catches, as an additional incentive for shifting to light-based SPS fishing.

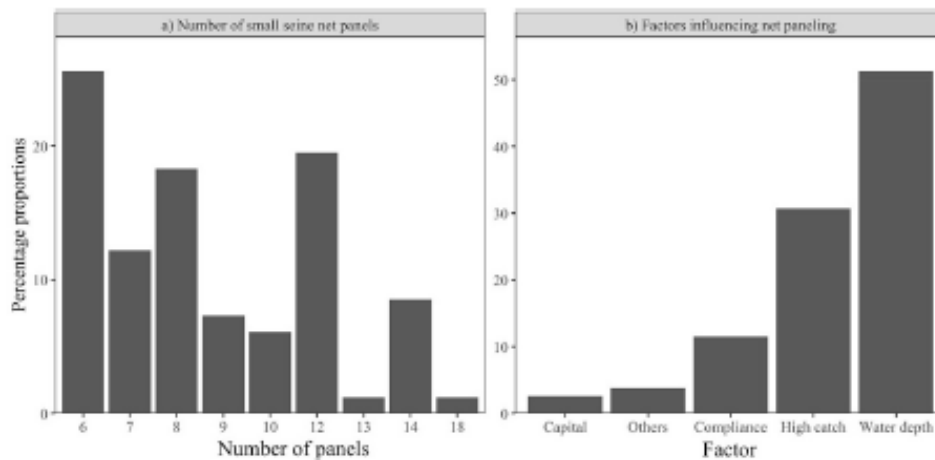


Fig. 3. Percentage of respondents reporting distribution of joined net panels per boat (a) and factors influencing net panelling (b) in small pelagic species (SPS) light-based fishery on Lake Albert. Data are from SPS fisher respondents ( $n = 41$ ).

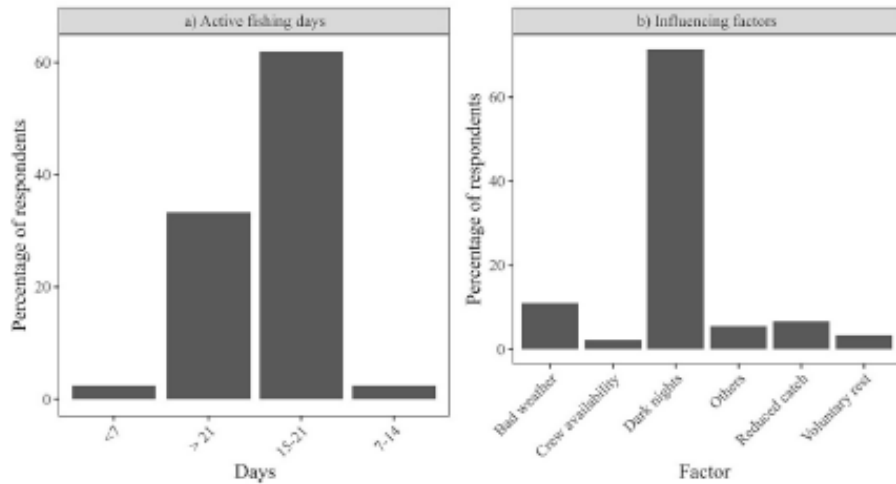


Fig. 4. Percentage of respondents reporting active fishing days per month (a) and the factors influencing their fishing activity (b) on Lake Albert. Data are from SPS respondents (n = 41).

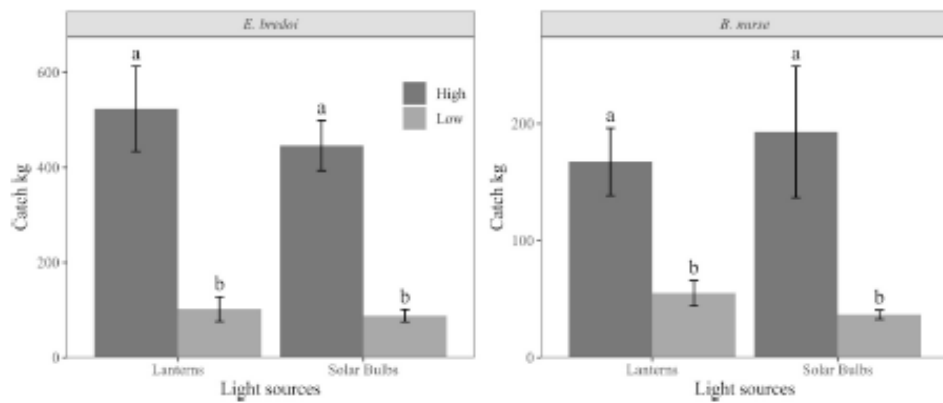


Fig. 5. Reported catch rates (catch-per-unit-effort) of *E. brederi* and *B. murie* by seasons (high- and low-catch production) and light sources (solar-powered and kerosene-powered lights) on Lake Albert. Letters a and b indicate significant differences ( $p < 0.05$ ) between high and low seasons for each respective light source, as determined by ANOVA. Data are from SPS respondents (n = 41).

3.9. Challenges faced by the SPS light-fishery on Lake Albert, Uganda

In addition to inter-gear conflict, SPS fishers highlighted several operational challenges. The most pressing concern was theft and destruction of fishing gear, including small-seine nets, fishing lights, and outboard engines, often attributed to perpetrators from the DRC side of the lake, cited by 72.5 % of respondents (Fig. 6). Other challenges include extreme weather conditions (13.8 %) and low fish prices (6.2 %). These challenges collectively were perceived to pose significant threats to the profitability and sustainability of the SPS fishery.

3.10. Management measures proposed by respondents for sustainable management of light-based SPS and LS fisheries in Lake Albert

Respondents from both LS and SPS proposed a range of management interventions aimed at resolving inter-gear conflict and enhancing the long-term sustainability of Lake Albert’s multispecies fishery. These insights were gathered through structured interviews, FGDs, and KIs, where respondents were asked about their perceived solutions to de-escalate conflict related to the SPS light-based fishery, while ensuring overall sustainability of the multi-species fishery. The proportion

reported below reflects support within each fisher group (LS or SPS).

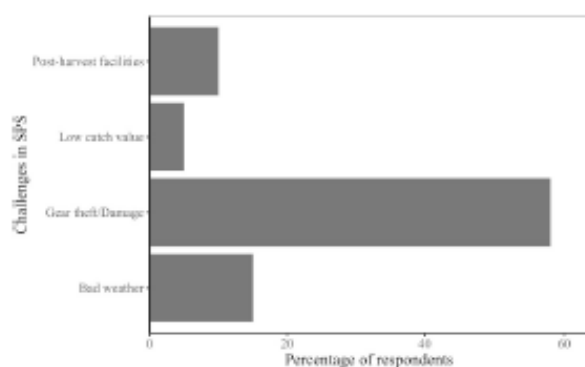
The most widely proposed measure was regulating SPS fishing effort, specifically limiting the number of fishing boats, net panels, and light intensity, supported by 60 % of LS respondents and 38 % of SPS respondents (Fig. 7a). Other proposed measures included:

- Closed season/fishing holidays: favoured by 77 % of LS vs. 27 % of SPS fishers
- Catch control limits: supported by 85 % of LS vs. 8 % of SPS fishers
- Designated exclusion zones: suggested by 53 % of LS vs. 10 % of SPS fishers
- Gear and mesh size restrictions: proposed by 80 % of SPS vs. 28 % of LS fishers, highlighting the urgent need to eliminate undersize and illegal gillnets widely used on the lake, which significantly contribute to the bycatch of juvenile LS.

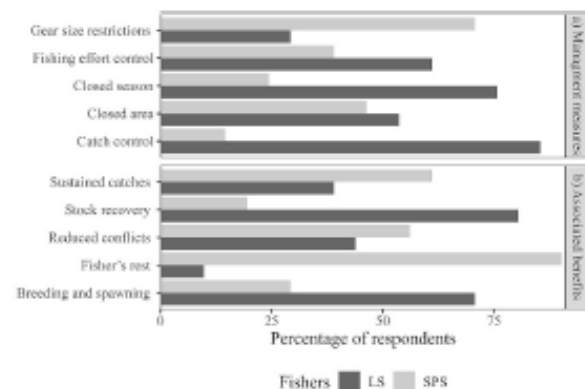
FGDs and KIs strongly supported these measures as effective strategies for reducing conflict and aiding the recovery of fish stocks. Among those in favour of closed seasons and fishing holidays, 93.4 % recommended aligning them with the full moon period, a time when light-based fishing is naturally reduced. This recommendation reflects

**Table 6**  
Perceived socio-economic and ecological factors driving the transition from traditional to light-based small pelagic species (SPS) fishing gears in Lake Albert.

Factors identified	Respondents			%
	LS (n = 41)	SPS (n = 41)	Total (n = 82)	
Reduced catch rates in of traditional legal fishing gear (gillnets and hooks)	30	34	64	78.0
Higher catch rates of SPS fishing gears	36	38	74	90.2
High operational costs associated with traditional legal fishing gear (gillnets and hooks)	26	30	56	68.3
High bycatch of large species in the SPS catch	32	16	48	58.5
Theft/destruction/loss of traditional legal fishing gear (gillnets and hooks) and catch	18	36	54	65.9
Frequent loss of traditional legal fishing gear (gillnets and hooks)	8	28	36	43.9
Intensified fisheries enforcements targeting illegal fishing activities	16	26	42	51.2
Allows fishers to rest for some days during full moon	8	12	20	24.4



**Fig. 6.** Percentage of respondents reporting challenges and constraints faced by the SPS light-based fishery on Lake Albert. Data are from SPS respondents (n = 41).



**Fig. 7.** Perceived management measures proposed for the sustainability of fisheries resources in Lake Albert (a) and their expected benefits (b). Data are presented as the percentage of large species (LS) fishers (dark grey bars) and small pelagic species (SPS) fishers (light grey bars) who responded (n = 82).

traditional practice, where most fishers voluntarily pause light-based fishing activity for about a week during the full moon. It also coincides with a similar closed season reportedly enforced on the DRC side; however, specific details regarding its timing and rationale could not be verified due to a lack of documented literature. Notably, respondents reported a significant influx of fishers from the DRC to the Uganda side during such closures.

Perceived benefits of these proposed measures varied by fisher group (Fig. 7b). Among LS respondents, benefits included stock recovery (−85 %), improved breeding or spawning (−67 %), and sustained catches (−55 %). SPS respondents emphasized conflict reduction (−47 %), stock recovery (−50 %), and rest period (−20 %). PGD participants further proposed spatial and temporal zoning of fishing activities, suggesting the segregation of fishing grounds and scheduling distinct time slots or periods for LS and SPS fishing. One participant stated:

*“The fishing time for musiri/ragoi (Engraulicypris bredoi/Brycinus nurse) and the large-bodied species should be defined, for example, musiri/ragoi during the night and other species during the day.”*

Another respondent elaborated:

*“Since musiri/ragoi fishers largely operate during dark periods, they should be allowed to fish strictly for two weeks of the dark moon phase, during which LS fishers could rest, and vice versa.”*

While these recommendations reflect localized knowledge and conflict mitigation strategies, their feasibility requires dialogue and harmonization with prevailing practices and regulatory frameworks, including Uganda's Fish (Fishing) Rules (Government of Uganda, 2010). Given that fishing activity on Lake Albert, in line with other national territorial waters, predominantly occurs at night, such proposals must be carefully evaluated within the context of current operational norms and legal provisions.

## 4. Discussion

### 4.1. Drivers of light-based fishing expansion

Multiple factors have contributed to the intensification of light-based fishing in Lake Albert, driving divergent opinions, and generating conflicts among fishing groups. Chief among them is the perceived decline in catches of large-bodied species, often attributed to heightened fishing pressure on traditional stocks. Additionally, stricter enforcement of regulations against illegal fishing, frequent gear losses, and the high operational costs of passive gears have pushed fishers towards alternative methods.

The rise of SPS light-based fishing has been particularly appealing due to perceptions of higher catch rates, interpreted as indicators of greater abundance. The incidental capture (bycatch) of large, high-value species during SPS operations provides an economic incentive, as these fish are sold separately at premium prices. The lower daily costs of operating solar-powered lighting systems compared to traditional sources further reinforce their attractiveness, especially for small-scale fishers. These trends mirror earlier findings from Lake Albert (Kolding et al., 2019; Mbabazi et al., 2012; Nakiyende et al., 2013, 2023a) and other African Great Lakes such as Lakes Victoria, Tanganyika, and Malawi (LVPO, 2022; Mgana et al., 2019; Taabu-Munyaho et al., 2016).

### 4.2. Evolution of fishing practices and gear use

Historically, Lake Albert's fishery was subsistence-based, targeting large-bodied characiform species like *C. citharus*, *H. forskahlii*, *A. baremose*, and *Distichodus niloticus* (Nile distichodus) (Holden, 1963; Worthington, 1929). Traditional gears included large-mesh gillnets, beach seines, baited longlines, and basket traps. However, population growth and increased fish demand have led to a surge in artisanal fishing

effort and gear diversification, including cast nets, boat seines, and small-mesh gillnets (Mbabazi et al., 2012; NaFIRRI, 2012; Nakiyende et al., 2013, 2023a, 2023b), some of which are prohibited under current regulations (Government of Uganda, 2010).

Since the early 2000s, the adoption of illuminated small seine nets targeting SPS has intensified (Mbabazi et al., 2012; Nakiyende et al., 2023a, 2023b). This gear evolution reflects a broader pattern in African inland fisheries, where fishing pressure drives adaptive shifts toward underexploited species and smaller size classes, consistent with the principles of balanced harvesting (Garcia et al., 2016; Kolding et al., 2016; Zhou et al., 2019). However, without effective management, this shift may further endanger vulnerable large-bodied species. Historical declines in *C. ciliaris*, *H. forskahlii*, *A. baremose*, and *D. niloticus* have been linked to excessive fishing effort and the rise of modern gillnet fisheries (Cadwalladr and Stoneman, 1966; Holden, 1963; Nakiyende et al., 2013; Von Sarnowski, 2004).

#### 4.3. Conflict and regulatory gaps

The emergence of the SPS light fishery has sparked tensions, especially between SPS and LS fishers. Conflicts revolve around access to fishing grounds, gear interference, declining catches, and the perceived ecological effects of light-based fishing practices. These reflect broader governance challenges and divergent views on sustainability. Uganda's current regulations for SPS fishing are minimal, limited to specifying an 8-mm mesh size (Government of Uganda, 2010), without covering critical factors such as net panel configuration, light type, or light intensity, which are central to ongoing conflicts between fishing groups. In the absence of empirical data, stakeholder perceptions and positions remain subjective and unaligned.

Key concerns include entanglements between passive and active gears (e.g., gillnets and light rafts) and the unregulated expansion of SPS boats and netpanel configurations, which may increase juvenile bycatch and harm demersal species and benthic habitats. Although actively operated gears like bottom trawls have documented impacts on lakebed ecosystems (Buhl-Mortensen and Buhl-Mortensen, 2018; Jones, 1992), similar studies on illuminated small seine nets in Lake Albert are lacking, hindering effective management. Another unresolved issue is the bycatch of juvenile LS, particularly Nile perch, linked to excessive net panelling and high-intensity lighting (number of lamps/bulbs). Stakeholders reported that solar lights increase gear visibility, causing avoidance behaviour among larger, more cautious fish.

Despite ongoing debates, empirical data on the extent of bycatch across different net panel configurations, light sources, and light intensities remain limited. This gap hinders the identification of optimal combinations that could maximize SPS catches while minimizing the bycatch of LS.

From stakeholder perspectives, there is a growing consensus that current regulations such as those in the Fish (Fishing) Rules (Government of Uganda, 2010) are insufficient to address the complex sustainability challenges facing the SPS fishery. Stakeholders emphasized the urgent need for additional management measures, including: (i) fishing effort control, encompassing limits on the number of fishing boats, net panels, and specifications for light source type and intensity; (ii) gear size restrictions, to reduce juvenile bycatch and protect early life stages of LS; (iii) catch control, informed by maximum sustainable yield estimates; (iv) closed areas, to protect ecologically critical habitats such as spawning and nursery grounds; and (v) introduction of closed seasons or fishing holidays, to enable stock recovery during key reproductive periods.

While these proposed measures are consistent with the FAO's Code of Conduct for Responsible Fisheries (FAO, 1995) and the ecosystem-based approach to fisheries management (Morishita, 2008), their implementation requires robust scientific data to inform policy design. Key data gaps include biological reference points (e.g., maximum sustainable yield, allowable fishing effort), gear selectivity, seasonal

dynamics in catch composition, reproductive biology, life-history traits, and habitat utilization (Lawrence et al., 2023; Nakiyende et al., 2023a, 2023b). Currently, such data are lacking for many target species in Lake Albert, including the SPS (Nakiyende et al., 2013, 2023a).

Although a fishing holiday is reportedly observed on the DRG side of the lake, its enforcement, effectiveness, and legal basis remain unclear. Given the transboundary nature of Lake Albert, there is a justifiable need for harmonized, bilateral fisheries management to guide coordinated efforts, such as seasonal closures and gear standardization. Without such cooperation, the sustainability of the SPS fishery and broader ecological balance of Lake Albert will remain under threat.

#### 4.4. Perception divides and technical considerations

SPS value chain actors favour solar lights due to their affordability, efficiency, environmental sustainability, and convenience, benefits echoed in studies on other large lakes (McHenry et al., 2012, 2014; Mgana et al., 2019; Mills et al., 2014; Solomon and Ahmed, 2016; Tian Hua and Xing, 2013). In contrast, LS actors targeting species like Nile perch and *A. baremose* oppose solar lights, citing gear avoidance and increased bycatch of juvenile fish. The fishers associated with LS have called for restrictions on SPS light fishing, citing violations of Uganda's prohibition of active fishing gears (Government of Uganda, 2010). Their advocacy led to a ministerial directive banning SPS fishing with small seine nets (commonly referred to as "hurry-up" nets due to their rapid deployment) and the use of solar lights (Harvest Money, 2024a; Daily Monitor, 2024b; Uganda Radio Network, 2006). However, from the SPS fishers' perspective, illuminated seine nets remain the only practical method for effectively targeting SPS shoals. As a result, they have protested the directive (Africa-Press, 2024; Harvest Money, 2024b; Monitor, 2024; The Cooperator News, 2024; Uganda Times, 2024).

Moreover, attempts to reintroduce alternative fishing methods such as illuminated ring scoop nets (chota-chota), previously used on Lake Victoria (Wandera, 1993, 2005), have had limited success due to challenges including rough offshore conditions and non-compliance with habitat protection regulations (Government of Uganda, 2010). These nets were largely abandoned during the early development of the SPS fishery and are mainly suitable for inshore shallow waters, as they lack the robustness to withstand the harsh weather and wave action in offshore deep waters. Furthermore, their use in shallow habitats contravenes existing regulations aimed at protecting critical fish habitats, such as spawning and nursery grounds (Government of Uganda, 2010; Nkalubo et al., 2018). Studies from Lake Victoria, where a similar fishery for *R. argentea* exists, show reduced bycatch in offshore waters (> 20 m depth) (Mangeni-Sande et al., 2019). However, the deployment of illuminated lift nets, whether twin boats (commonly catamarans) or fixed fishing rigs, has shown limited feasibility on Lake Victoria despite being technically compatible with offshore deep-water fishing (Wandera, 2005). The major constraints are their high capital and operational costs.

Therefore, the persistent absence of clear regulatory provisions specific to SPS fishing methods in Uganda (Government of Uganda, 2010), beyond mesh size restrictions, continues to hinder the optimization of SPS fisheries, especially amid ongoing conflict with fishers targeting LS. There is an urgent need for targeted research to develop and evaluate alternative fishing technologies that reduce bycatch of large and juvenile species, while enhancing SPS harvest efficiency, offering a sustainable and conflict-sensitive path forward.

#### 4.5. Small-pelagic species catch dynamics, operational challenges, and post-harvest losses

Seasonal variation in the reported catch rates of *E. bredoi* and *B. nurse* is likely influenced by local weather patterns, with higher catches generally observed during rainy months (NEMA, 2016). Rainy periods are typically associated with increased food availability and breeding

activity (Castillo-Rivera, 2013; Ríos-Pulgarín et al., 2016), which enhance localized fish abundance and capture probability. Conversely, dry seasons often coincide with reduced catches, attributed to fish dispersal and lower biological productivity.

Beyond conflict-related issues, the SPS fishery on Lake Albert faces multiple operational constraints. These include adverse weather conditions, cross-border incursions by fishers from the DRC, and significant post-harvest losses, which have been reported to reach up to 40% (Efitre et al., 2023). These losses result primarily from inadequate handling and storage infrastructure at landing sites. Poor-quality fish, often caused by spoilage or unhygienic handling, are commonly diverted to the animal feed market rather than human consumption (Nordhagen, 2021). Addressing this challenge requires targeted investments in cold chain infrastructure, improved drying technologies, and stronger market linkages. Strategic interventions should therefore focus on enhancing infrastructure, building capacity in value addition, and developing stronger market connections. Furthermore, awareness campaigns and training in water safety and use of life-saving gear are critical for safeguarding fishers during poor weather conditions (Oporia et al., 2022). Additionally, active engagement of fisher communities in co-management and decision-making is essential, as supported by global best practices (Ban et al., 2017; Butler et al., 2012).

## 5. Conclusion and recommendations

This study revealed that the promising potential of a light-based small pelagic species (SPS) fishery in Lake Albert is significantly constrained by persistent fishing conflicts. These disputes are largely driven by divergent stakeholder perceptions, particularly between fishers targeting large-bodied species (LS) and those engaged in the SPS value chain. These are further intensified by a critical lack of empirical data on multispecies ecosystem dynamics. This complex interplay underscores the urgent need for a more informed, evidence-based, and collaborative approach to fisheries management.

A key finding is the knowledge gap and lack of empirical research to guide sustainable exploitation of SPS resource. Specifically, robust data are required on optimal fishing effort, net panel configurations, light type, and intensity, to minimize bycatch and support the establishment of scientifically informed harvest limits. Further research is also needed to evaluate gear configurations and selectivity, quantify bycatch composition, and assess habitat impacts, which are all areas currently lacking in rigorous scientific evidence. Additionally, the seasonal variability of SPS catch rates observed during this study warrants targeted ecological investigations to support spatial-temporal management strategies.

The findings also highlight the necessity of moving beyond simplistic regulatory measures such as mesh size limits. While many stakeholders demonstrate an awareness of sustainable practices, consistent with the FAO's Code of Conduct for Responsible Fisheries (FAO, 1995) and the Ecosystem-Based Approach to Fisheries Management, these are often not reflected in current regulations due to the lack of scientific data on most exploited stocks. This regulatory gap has contributed to the escalation of fishing-related conflicts.

The widespread use of illegal fishing gears by both LS and SPS fishers, as documented by Mbabazi et al. (2012), NaFIRRI (2012), and Nakiyende et al. (2023a), further complicates effective management. Addressing this issue requires not only strengthened enforcement by the Directorate of Fisheries Resources (DiFR) under the Ministry of Agriculture, Animal Industry and Fisheries (MAAIF), but also the active involvement of local communities through co-management and self-regulation mechanisms.

Ultimately, the sustainable management of Lake Albert's multispecies fisheries ecosystem demands an integrated approach, anchored in robust scientific research, adaptive fisheries governance, stakeholder engagement, and post-harvest system improvements. Key priorities include upgrading post-harvest infrastructure, building local capacity in

value addition, and enhancing market linkages to improve the economic and nutritional value of SPS, whose potential is currently underutilized due to high post-harvest losses.

Lastly, given Lake Albert's transboundary nature, cross-border harmonization with the Democratic Republic of the Congo is essential. Coordinated efforts in implementing measures such as seasonal closures and gear regulations will be critical to ensuring effective and sustainable fisheries management. By adopting these integrated strategies, the diverse communities dependent on Lake Albert can navigate the current challenges and move toward a future of peaceful co-existence and long-term sustainability within this vital fishery.

## Data availability

The data for this manuscript has not yet been posted in any repository but will be available on request.

## CRediT authorship contribution statement

Herbert Nakiyende: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. Jackson Efitre: Writing – review & editing, Validation, Supervision, Project administration, Conceptualization. Anthony Basooma: Writing – review & editing, Visualization, Methodology, Formal analysis. Mbilingi Bwambale: Writing – review & editing, Methodology, Investigation. Dismas Mbabazi: Writing – review & editing, Writing – original draft, Validation, Methodology. Joyce Akumu: Writing – review & editing, Methodology, Investigation. Veronica Mpomwenda: Writing – review & editing, Methodology. Winnie Nkalubo: Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Funding acquisition. Anthony Taabu-Munyaho: Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Conceptualization. Samuel Basso: Writing – review & editing, Validation. Esther Kagoya: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. Bairon Mugeni: Writing – review & editing, Visualization. Gladys Bwanika: Writing – review & editing, Supervision, Conceptualization. Lauren Chapman: Writing – review & editing, Validation, Supervision, Methodology.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors further declare that none of its members is an Editorial Board Member/Editor-in-Chief/Associate Editor/Guest Editor. However, we would like to point that Dr. Ogutu-Ohwayo, one of the editors of Great Lakes Research Journal, has previously worked with and supervised some of the authors during his tenure at the National Fisheries Resources Research Institute (NaFIRRI). We affirm that this professional relationship does not influence the content or conclusions presented in this manuscript.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jglr.2025.102664>.

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## **CHAPTER FIVE: SPATIAL AND TEMPORAL DISTRIBUTION OF THE TWO SMALL PELAGIC SPECIES (ENGRAULICYPRIS BREDOI AND BRYCINUS NURSE) AND LIGHT FISHING EFFORT IN LAKE ALBERT.**

### **CONTEXT**

This chapter examines the fundamental drivers of the ecological distribution and catchability of *Engraulicypris bredoi* and *Brycinus nurse* and light-assisted fishing effort in Lake Albert. The ecological distribution and catchability of *Engraulicypris bredoi* and *Brycinus nurse* in Lake Albert are fundamentally governed by lunar periodicity. Hydroacoustic assessments and spatial mapping reveal that light-assisted fishing effort is now a lake-wide phenomenon, spanning the entire Ugandan shoreline. However, species distribution exhibits significant regional variation: *E. bredoi* maintains a higher biomass in the central region of the lake, while *B. nurse* is most abundant in the northern and southern sectors. This spatial heterogeneity suggests that "blanket" management may be less effective than region-specific interventions tailored to the dominant species' biological requirements.

The study establishes a direct correlation between natural illumination and fishing intensity. During dark lunar phases (New Moon), artificial light-attraction efficiency is maximized, leading to a densification of fishing effort in deep offshore waters (exceeding 20 meters). These periods coincide with peak catch rates and a high degree of species selectivity. Conversely, the full moon phase introduces a "lunar illumination effect" that dissipates fish schools throughout the water column, causing a precipitous drop in catchability.

Despite this biological dispersal and reduced technical efficiency, a significant portion of the fishing fleet persists in "continuous fishing" throughout the lunar cycle. During bright phases, effort shifts from productive offshore waters to shallow inshore habitats (less than 20 meters). This localized concentration of light-assisted gear in inshore zones is particularly destructive, as it penetrates critical breeding and nursery grounds, significantly increasing the incidental capture of juvenile large-bodied species.

To address this misalignment between effort and ecology, the study advocates for a dual management approach grounded in Temporal and Spatial Closures. First, the adoption of a Lunar-Synchronized Fishing Calendar is essential to formalize the full moon period as a mandatory "rest holiday." This intervention would effectively reduce annual fishing mortality (\$F\$) without

compromising the periods of highest economic productivity. Second, the evidence justifies a Complete Spatial Closure of shallow inshore habitats to all light-based gear and human-related disturbances. Protecting these inshore refugia is critical for safeguarding spawning stocks and ensuring the long-term recruitment of both target small pelagics and the multispecies complex of Lake Albert.

The detailed chapter is presented below as a publishable article under the title “Spatial–temporal responses of light-based small-pelagic-species fisheries to lunar cycles in Lake Albert: Implications for sustainable management.”

## **ABSTRACT**

Small pelagic species (SPS), including sardines, anchovies, herrings, and cyprinids, underpin food security and livelihoods globally, sustaining some of the most productive marine and inland fisheries. Their behavioral sensitivity to light and lunar cycles influences availability and catchability, yet the management implications of these dynamics remain underexplored, particularly in data-limited tropical inland systems such as Lake Albert. This study uses Lake Albert (East Africa) as a case study to examine the factors that influence the spatial–temporal dynamics of SPS fisheries. Drawing on geospatial mapping, catch assessment, and hydroacoustic surveys, the study examined the distribution and fishery responses of *Engraulicypris bredoi* and *Brycinus nurse*, which together contribute ~70% of Lake Albert’s annual yield.

Results revealed that lunar periodicity had the most pronounced effects on fishing effort and fish distribution, with both effort and catch rates peaking during moonless nights and declining sharply under full-moon illumination. Spatially, *E. bredoi* aggregated in deeper central-basin waters, while *B. nurse* occupied shallower, vegetated northern and southern habitats. Hydroacoustic backscatter confirmed the dominance of SPS, accounting for ~80% of total pelagic biomass.

These findings underscore the role of lunar cycles as critical drivers of SPS fisheries and demonstrate the value of integrating lunar metrics into stock assessments and management strategies. The study highlights broader implications for similar light-based SPS fisheries, including the potential utility of lunar-based fishing calendars, adaptive effort controls, and cross-border governance frameworks. Embedding lunar dynamics in ecosystem-based fisheries management could enhance

stock sustainability, reduce pressure, and improve resilience of small pelagic resources that support millions of livelihoods globally.

**Keywords:** African Great Lakes, *Engraulicypris bredoi*, Light fishing, Lunar-based closures; Small pelagic species.

## 5.1. INTRODUCTION

Small pelagic species (SPS) support some of the world's most important fisheries, both in marine and inland waters, and their exploitation is often closely linked to lunar periodicity. Globally, SPS such as sardines, anchovies, herrings, and cyprinids form the backbone of food security and livelihoods for millions of people (Cooke et al., 2017; Nguyen & Winger, 2019; Alheit and Peck, 2019; Nhat et al., 2023). In tropical systems, lunar cycles strongly influence diel vertical migrations, aggregation behaviour, and catchability, with light fishing emerging as a dominant strategy to optimize harvests during darker nights (Arimoto et al., 2007; Nightingale et al., 2006; Pulver, 2017). These dynamics are not unique to any single water body but represent a widespread challenge and opportunity in balancing harvest efficiency with long-term sustainability. Despite their global significance, SPS light fisheries remain under-studied in inland waters, where data limitations often hinder adaptive management.

Lake Albert, a transboundary water body shared by Uganda and the Democratic Republic of the Congo (DRC) (Hamilton et al., 2022), hosts Uganda's second-largest artisanal fishery after Lake Victoria (Mbabazi et al., 2012; LVFO, 2022; Nakiyende et al., 2023a). Since the early 2000s, the artisanal fishery has shifted toward dominance by two small pelagic fish species (SPS), *Engraulicypris bredoi* and *Brycinus nurse*, which together contribute over 70% of the annual catch, estimated at ~340,000-tonnes (Mbabazi et al., 2012, 2019; Kolding et al., 2019; Nakiyende et al., 2023). These species are primarily harvested using artificial light attraction during dark nights (NaFIRRI, 2012a, 2012b, 2021b; Nakiyende et al., 2023), reflecting both their behavioural sensitivity to light and the adaptive strategies of fishers responding to lunar cues (Hammerschlag et al., 2017; Regular et al., 2021; Andrzejczek et al., 2024).

The role of lunar illumination as a fundamental driver of spatial-temporal catch patterns has been well documented in both marine and inland SPS fisheries (Demirci & Şimşek, 2025; Arimoto, 2013; Nguyen & Winger, 2019). Moonlight influences vertical migration and aggregation, thereby directly shaping the efficiency of light-attraction gears. During darker lunar phases, reduced

illumination enhances the effectiveness of artificial lights in concentrating and aggregating fish near the surface, while brighter full moons disperse schools and reduce catchability (Pulver, 2017; Nhat et al., 2023). Fishers exploit these ecological windows by deploying artificial illumination sources such as solar lamps, kerosene lamps, or other devices to attract fish, which are subsequently harvested with small seine or lampara nets (Nightingale et al., 2006; Becker et al., 2013).

On Lake Albert, the light-based SPS fishery is characterized by distinct vessel types, propulsion systems, lighting technologies, gear configurations, and fishing effort patterns (Table 5.1-1). Two vessel types dominate: the Congo barque (CB) and the Ssesse flat-at-one-end (SF) boat, propelled either by outboard engines or paddles (NaFIRRI, 2021b; Nakiyende et al., 2023b). Fishing operations rely exclusively on artificial light, primarily solar-powered bulbs (SPB) or kerosene pressure lamps (KPL). Each vessel typically mounts three to four rafts per vessel, with SPB units deploying up to 16 bulbs compared to only three lamps for the KPL units (NaFIRRI, 2021b). The main gear used is a small-seine net (5–6 mm mesh size), with configuration varying by vessel propulsion and lighting technology (Mbabazi et al., 2012, 2019; Nakiyende et al., 2023b).

**Table 5.1-1.** Operational characteristics of small pelagic light-based fishing effort indicators on the Uganda side of Lake Albert. Source: Frame Survey Technical Report (NaFIRRI, 2018; 2021b). SPB = Solar powered bulbs, KPL = Kerosene lamps, SS = small seine nets.

<b>Fishery Characteristic</b>	<b>Variable Measure</b>
Fishing Vessel	Congo barque, Ssesse flat-at-one-end
Propulsion Mode	Outboard engine, Paddles, Towed
Fishing Light	SPB (Solar-powered bulbs), KPL (Kerosene lamps)
No. of Rafts per Vessel	3–4
No. of Lights per Raft	SPB: 3–4 bulbs; KPL: 1 lamp
No. of Lights per Vessel	Range from 3 (KPL) to 16 (SPB)
Fishing Gear	Small Seine (SS)
Mesh Size (mm)	5 mm - 6 mm
Average Number of SS Panels per Vessel	7–12
Range of SS Panels per Vessel	4–20
Crew per Vessel	3
Fishing Days per Month	21 (up to 30 for some SF–SPB units)

SPS fishing effort on Lake Albert, like many African Great Lakes (AGLs) such as Lakes Victoria, Tanganyika, Malawi, and Kivu is optimized during dark moon nights (Mgana et al., 2019;

LVFO, 2022, Nakiyende et al., 2023b), with some fishers withdrawing their gears during full moon nights. However, others continue operating across all moon phases, provided weather conditions permit (Nakiyende et al., 2025). Concerns have been raised about the continuous fishing, particularly among fishers targeting large-bodied species fishers, who argue that uninterrupted SPS harvest elevates bycatch of large, especially during full moon months. They further contend that this practice conflicts the traditional fishing norms in which light fishing was restricted to approximately three weeks of dark nights, with full moon periods reserved for alternative livelihood activities such as farming. Such rotational practice is reported historically to have facilitated stock recovery, reduced inter-group conflicts, and promoted harmony between SPS and large-bodied fisheries (*personal comm.*).

Despite their ecological and economic importance, the population dynamics and catch patterns of SPS in Lake Albert remain underexplored, particularly in relation to lunar cycles and artificial lighting. Research on this lake has historically focussed on large-bodied commercial species such as *Lates niloticus*, *Alestes baremoze*, *Hydrocynus forskahlii*, and *Bagrus bajad* (Mbabazi et al., 2012; Nakiyende et al., 2013; Matunguru et al., 2023). In contrast, SPS—though they now dominate catches and likely contribute most of the pelagic biomass, have received comparatively little scientific attention (Efitre et al., 2023). Existing knowledge on the two dominant SPS (*Engraulicypris bredoii* and *Brycinus nurse*) in Lake Albert is limited to assessments of their catch, effort, and partially population structure (Namboozo, 2008, Nakiyende et al., 2023a, 2023b, 2025), with vital ecological aspects such as lunar-species interactions, behavioural dynamics, and spatial–temporal variability remaining poorly understood.

Understanding these dynamics is essential for developing sustainable management strategies, including effort regulation, seasonal closures, and spatial planning (Poisson et al., 2010; Chakraborty, 2020; Jose et al., 2022; Cerim et al., 2023). This study uses Lake Albert as a case study to investigate lunar-driven dynamics in a tropical inland SPS fishery, while situating the results in the broader context of artisanal light-based fisheries across similar AGLs ecosystems and beyond. By doing so, the study contributes to the design of adaptive, ecosystem-based management strategies that can simultaneously support food security, sustain livelihoods, and mitigate risks of overexploitation in data-limited fisheries. More broadly, insights into the interplay between lunar periodicity, fishing technology, and SPS behaviour are increasingly relevant for the AGLs such as Victoria, Tanganyika,

Kivu, and Malawi, where light-based SPS fisheries form the backbone of production, but management faces persistent challenges (Guillard et al., 2012; Kolding et al., 2019; Mbabazi et al., 2012; Mgana et al., 2019; Nakiyende et al., 2023a, 2023b, 2025).

## **5.2. MATERIALS AND METHODS**

### **5.2.1. Study area**

The study was conducted in the Ugandan sector of Lake Albert (see **Figure 1.7-1**), an area renowned for its intensive light-based fishery targeting *E. bredoi* and *B. nurse* (Mbabazi et al., 2012; NELSAP, 2019; Nakiyende et al., 2023a; 2023b). A multi-method sampling design incorporating hydroacoustic surveys, geospatial surveys, and Catch Assessment Surveys (CASs) was employed to characterize the spatial-temporal dynamics of these SPS (Creswell and Tashakkori, 2007; Creswell, 2014; LVFO, 2019). Lake Albert's habitats were classified based on Hamilton et al. (2022) into: shallow inshore (<20 meters deep), mid-shore coastal (20-40 meters deep), deep offshore (>40 meters deep), and lagoons, bays, and river inlets.

To capture spatial heterogeneity, the lake was stratified into three zones (northern, central and southern) consistent with previous assessments from 2007 – 2021 (NaFIRRI, 2021a).

1. **Northern region:** Pakwach and Buliisa districts (Murchison Nile-Delta to River Waaki)
2. **Central region:** Including Hoima and Kikuube districts (River Waaki to Nkondo)
3. **Southern region:** Encompassing Kagadi and Ntoroko districts (Nkondo to River Semiliki)

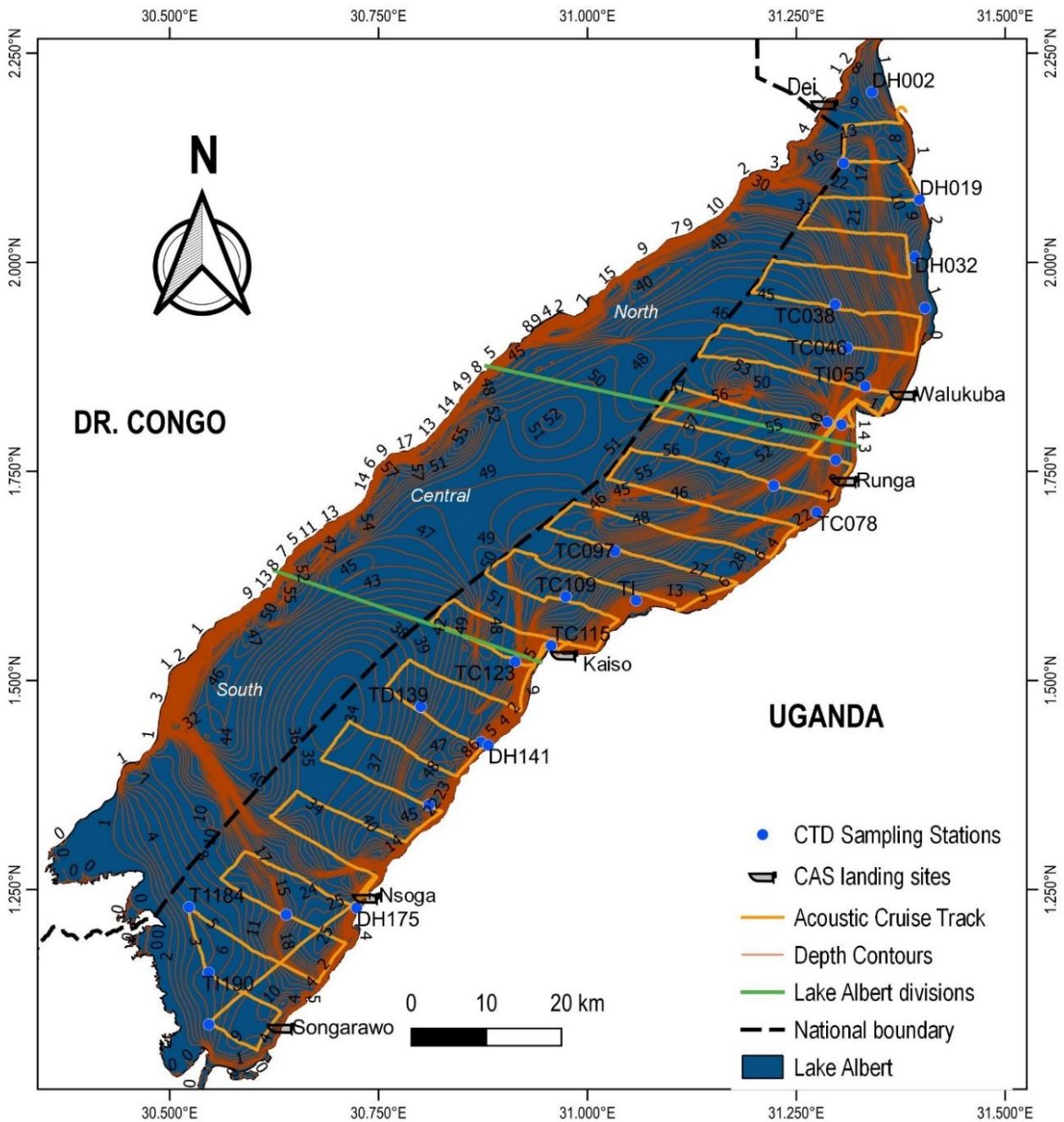
Historical datasets (2007-2022) on fishing effort and catch landings were also integrated to provide temporal depth.

### **5.2.2. Acoustic survey for mapping species abundance and distribution**

A lake-wide acoustic survey was conducted in September 2021, covering ~2850 km<sup>2</sup> of the Ugandan waters of Lake Albert (**Figure 5.2-1**). Transects were systematically laid across three regions and stratified by depth class: inshore ( $\leq 20$  meters), coastal/mid-water (20-40 meters), and deep offshore (>40 meters) (Hamilton et al., 2022). Data were collected aboard a twin-engine (40 & 75 HP) survey vessel operating at an average cruising speed of nine knots.

The survey vessel was equipped with a Simrad EK80 WBT split-beam echo-sounder system operating at 120 kHz mounted 1 meter below the water surface. Calibration was conducted using a 38.1 mm tungsten carbide sphere (TS -38.1 dB) in calm inshore waters near Kaiso landing site using

standard calibration split-beam protocol (Foote et al., 1987). Acoustic data collection followed LVFO hydroacoustic protocols (LVFO, 2022), and surveys were conducted between 0800 and 1800 hours. Parallel transects were spaced at 5-kilometre intervals. Fish targets were categorized by size as small pelagics (<13 cm TL) and large-bodied fish ( $\geq 13$  cm TL).



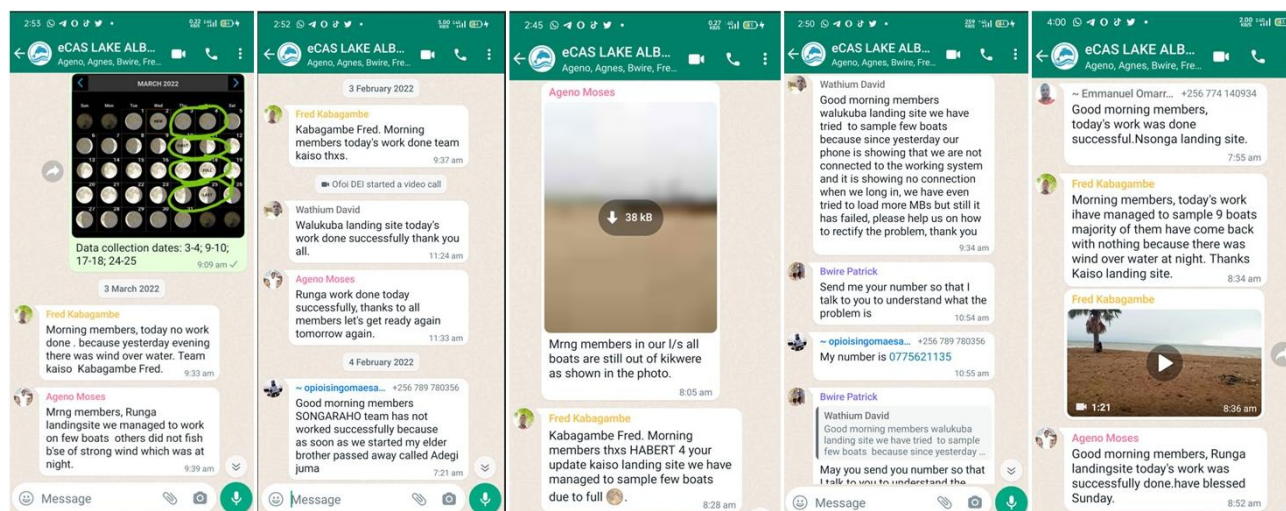
**Figure 5.2-1.** Acoustic cruise tracks and catch assessment survey sites sampled for data collection on Lake Albert, Uganda.

### **5.2.3. Geospatial surveys of fishing effort distribution**

To assess fishing effort distribution and vessel deployment, geospatial surveys were undertaken during new moon (total darkness) and full moon (maximum brightness) periods. Three field teams used GPS units to geo-reference active light-fishing units (rafts) observed at night across the lake. Effort data were supplemented with Frame Survey records from 2007–2019 and CAS records from NaFIRRI between 2007 and 2021 (Mbabazi et al., 2012; NaFIRRI, 2021a). Light-fishing technologies, including solar lamps, kerosene lanterns, and lampara nets, were documented in relation to depth strata and moon phases.

### **5.2.4. Catch Assessment Surveys of artisanal catches**

CASs were conducted at six strategically selected landing sites (**Figure 1.7-1**), two per region, based on documented SPS activity (NaFIRRI, 2021b): North (Dei and Walukuba), Central (Runga and Kaiso), and South (Nsonga and Songarawo). Monthly CASs were carried out between September 2019 and August 2022, with a COVID-19 related suspension between September 2020 and July 2021. Data collection followed LVFO (2019) protocols. At each site, 30 randomly selected boats were sampled per day over two consecutive days during each lunar phase: New Moon (N), First Quarter (Q), Full Moon (F), and Third Quarter (T). Trained enumerators recruited from within the landing site community recorded catch composition (species, volume), gear type, light source, and effort characteristics. Coordination was enhanced through a dedicated WhatsApp group for real-time troubleshooting and schedule dissemination (**Plate 5.2-1**). Moon phase schedules were sourced from [www.moongiant.com](http://www.moongiant.com).



**Plate 5.2-1. WhatsApp communication between enumerators and researcher during catch data collection on Lake Albert, Uganda.**

### 5.3. Data processing and analysis

#### 5.3.1. Species spatial distribution and abundance using acoustic surveys

Hydroacoustic data were processed and analysed using *Echoview* version 12.1 (Echoview Software Pty Ltd, 2021) to estimate the spatial distribution, relative abundance, and biomass indices of pelagic fish communities. The analysis employed two core methodologies: Echo integration for small pelagic species and Single Target Analysis (STA) for large-bodied individuals (Kayanda et al 2012, Nyamweya et al. 2023).

**Target classification and threshold:** Fish echoes were classified based on target strength (TS) thresholds. A minimum threshold of -50 dB was used to discriminate between small pelagic fishes and larger-bodied individuals (Kayanda et al., 2012; Taabu-Munyaho et al., 2014; LVFO, 2022). Echoes with  $TS \leq -50$  dB were interpreted as small pelagics, and quantified using echo integration, whereas Echoes with  $TS > -50$  dB were considered single targets representing large-bodied fishes and were analysed using the Single Target Split Beam Method 2 algorithm, which utilizes split-beam outputs of both power and angular position to resolve discrete individual echoes (Nyamweya et al., 2023).

**Data filtering and quality control:** To ensure analytical rigor, near-surface noise was minimized by setting a Topline exclusion at 3.9 m depth. Similarly, the Bottomline was set 0.5 m above the lakebed to exclude bottom dead zones and minimize signal interference (Nyamweya et al., 2023).

***Spatial segmentation and biomass estimation:*** The water column was divided into discrete sampling units known as Elementary Distance Sampling Units (EDSUs), with a vertical resolution of 2 m and a horizontal resolution of 1 km, following established guidelines (Getabu, 2003; Taabu-Munyaho et al., 2014). Transects shorter than 1 km were weighted proportionally in biomass estimation to account for reduced spatial coverage.

Backscatter data were integrated within each EDSU to estimate volume backscattering strength ( $S_v$ ), which was then converted into fish density estimates using appropriate target strength-to-length regression equations. This method provided a high-resolution spatial overview of species distribution and abundance patterns across the surveyed transects, enabling quantification of biological backscatter and robust biomass indexing of pelagic fish assemblages.

$$S_{vSingle\ targets} = TS_{mean} + 10\log N_{Targets} - 10\log V_{Beam} - 2.3 \quad (1)$$

The Area Backscattering Coefficient (ABC) for discrete fish targets was derived from volume backscattering strength values ( $S_v$ ) specific to single targets using a standard logarithmic transformation as shown in Equation 2 (LVFO, 2022):

$$ABC_{single\ targets} = 10^{(S_{vSingle\ targets}/10)} \quad (2)$$

Where:  $S_{vSingle\ targets}$  is the measured volume backscattering strength in decibels (dB re 1 m<sup>-1</sup> m<sup>-1</sup>) is associated with large-bodied individual fish detections.

Following this, the derived ABC values were scaled to the Nautical Area Backscattering Coefficient (NASC), a standardized metric used to express backscatter per unit nautical area, using equation 3:

$$NASC = 4\pi * (1852^2) * ABC_{single\ targets} \quad (3)$$

Where: NASC is expressed in square meters per nautical mile (m<sup>2</sup>/nmi<sup>2</sup>),

1852 represents the meters in one nautical mile, and

$4\pi$  represents the spherical spreading factor in underwater acoustics.

### **5.3.2. Echo integration for small pelagic species**

Echo integration was performed across defined vertical strata (from the Topline set at 3.9 m below the surface to the checked bottom line defined as 0.5 m above the substrate (**Plate 5.3-1**), to

quantify the backscatter attributed to small pelagic species. The Sv values were extracted for each EDSU, defined as 2 m vertical  $\times$  1 km horizontal segments, and organized by spatial location (transects and regions). These Sv values represent the intensity of acoustic energy reflected by aggregations of small pelagic fish.

**Conversion to area backscattering coefficient (ABC):** The Sv values attributed to small pelagic fish were converted into the Area Backscattering Coefficient (ABC) using the logarithmic relationship in Equation 4:

$$ABC_{small\ pelagics} = 10^{(Sv_{small\ pelagics}/10)}(4)$$

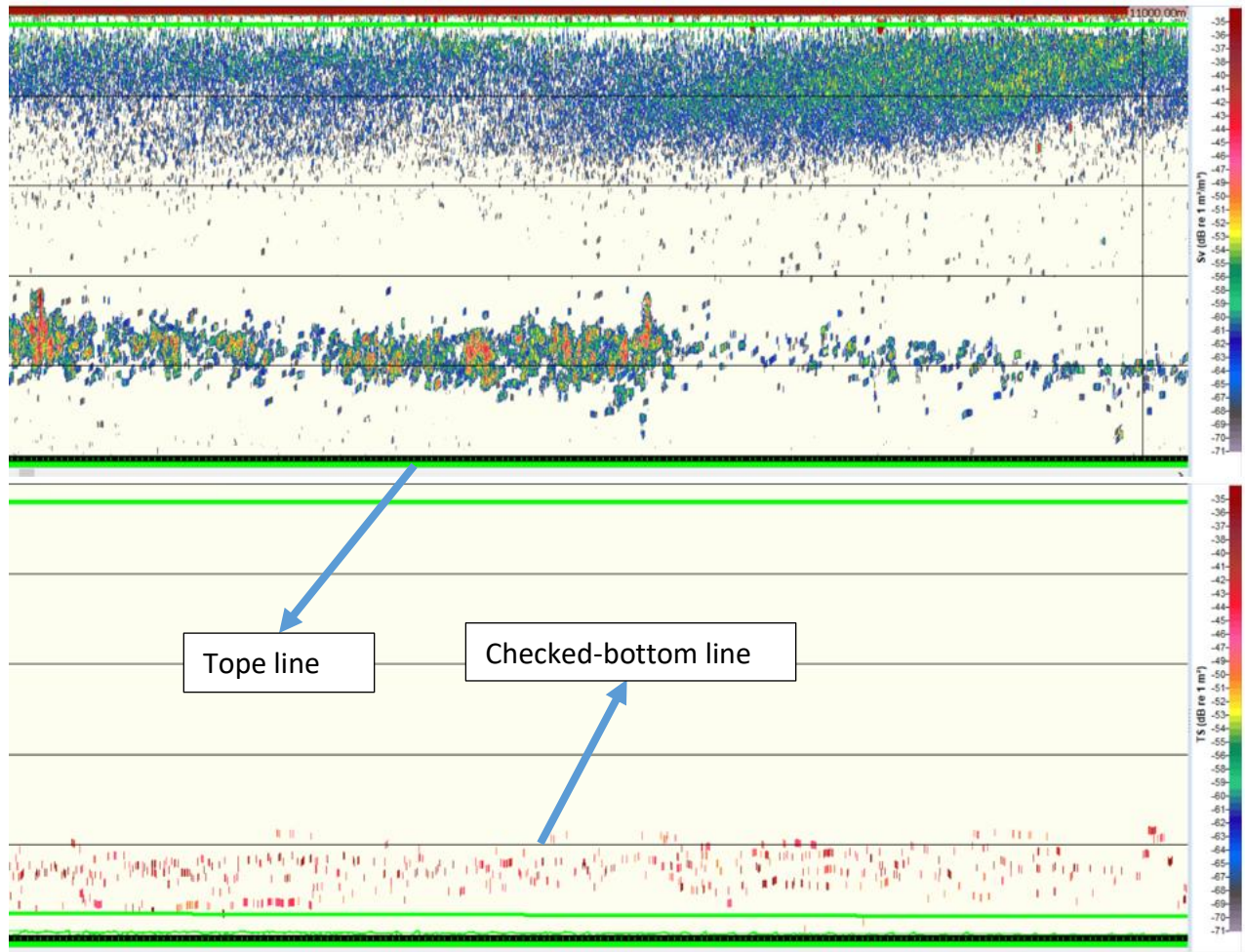
Where;  $Sv_{small\ pelagics}$  is the volume backscattering strength in decibels (dB re 1 m<sup>-1</sup> m<sup>-1</sup>).

**Integration across vertical layers:** ABC values from all vertical EDSUs within each sampling transect were summed to estimate total area density per unit horizontal distance, representing the cumulative backscatter contribution of small pelagic fish within the echo-integration layer.

**Scaling to nautical area scattering coefficient (NASC):** The integrated ABC values were scaled to the Nautical Area Scattering Coefficient (NASC) to express acoustic energy per unit nautical area, a standard metric in fisheries acoustics. NASC, typically expressed in square meters per nautical mile squared (m<sup>2</sup>/nmi<sup>2</sup>), facilitates inter-comparison of fish biomass estimates across space and time. This process enabled the derivation of quantitative indices of pelagic fish biomass and spatial distribution across the sampled regions of Lake Albert, providing robust input data for subsequent density and abundance estimation.

### 5.3.3. Fishing effort composition and distribution (geospatial analysis)

Geospatial maps illustrating the spatial distribution of SPS light-fishing effort along the Ugandan shoreline of Lake Albert, as well as the spatial-temporal deployment patterns of fishing lights during two contrasting lunar phases, new moon (total darkness) and full moon (maximum illumination), were developed using QGIS Version 3.12 (QGIS Development Team, 2018) and R software. This geospatial analysis provided a comprehensive visualization of the intensity and distribution patterns of SPS light-fishing effort across the Ugandan sector of the lake.



**Plate 5.3-1.** Echograms illustrating target strength and analysis lines. The top echogram displays Echo Integration, with analysis lines referenced to the water surface. The bottom echogram depicts single targets, with analysis lines referenced to the echosounder-detected bottom. The coloured legend on the y-axis represents target strength in decibels (dB).

#### 5.3.4. SPS catch rates across regions, months, and lunar phases

Catch Assessment Survey (CAS) data were used to evaluate the catch performance of the SPS light fishery. Catch per unit effort (CPUE), specifically for *E. bredoi* and *B. nurse*, was computed by lunar phase, region, and month, and expressed as kilograms per boat per day. The CPUE calculations followed standard formulas prescribed in LVFO (2019).

- CPUE ( $\text{kg boat}^{-1} \text{ day}^{-1}$ ) for each species  $s$  by region  $r$  was calculated as:

$$CPUE_{s,r} = \frac{C_{s,r}}{E_{s,r}} \quad (5)$$

Where  $C_{s,r}$  is the total catch (kg) of species  $s$  in the region  $r$ ,  $E$  is the total effort (number of boats) contributing to the total catch in the region.

- CPUE (kg boat<sup>-1</sup> day<sup>-1</sup>) for each species in each sampled in the month ( $m$ ) was calculated as:

$$CPUE_{s,m} = \frac{C_s}{E_s} \quad (6)$$

Where  $C_s$  is total catch (kg) of species  $s$  from all boats sampled,  $E_s$  is total number of boats contributing to the total catch.

- CPUE (kg boat<sup>-1</sup> day<sup>-1</sup>) for each species in each moon phase  $mp$  was calculated as:

$$CPUE_{s,mp} = \frac{C_s}{E_s} \quad (7)$$

**Note:** Samples from landing sites sampled in the region were pooled to estimate regional CPUE, while CPUEs by month and moon phase were based on samples from all sampled sites.

### 5.3.5. Estimation of monthly and annual total catch

The total monthly catch ( $t$ ) for each study species by sampled month  $m$  was calculated as:

$$C'_{vg,s,m} = CPUE_{s,m} \cdot X'_{vg,s} \cdot BAC_{vg,m} \cdot AD_{vg,m} \quad (8)$$

Where;  $C'_{vg,s,m}$  = Catch of species,  $X'_{vg,s}$  = Number of boats targeting species,  $AD_{vg,m}$  = Active days fished in a month,  $BAC_{vg,m}$  = Boat activity coefficient,  $s$  = Species,  $m$  = Month,  $vg$  = vessel-gear types (boats).

The Boat Activity Coefficient ( $BAC$ ) quantifies the likelihood that a specific vessel-gear ( $v-g$ ) type will be active on any given day of the month. It is calculated as the mean number of days boats in each effort group fished in a week divided by the number of days in a week multiplied by 30 days in a month.

The total annual catch ( $t$ ) for each species was calculated as the sum of the monthly catch for all sampled months within a year, expressed as:

$$C_{s,y} = \sum_{vg} \sum_m \sum_y C'_{vg,s,m} \quad (9)$$

To account for annual variation, data were analyzed separately for each year, allowing identification of inter-annual trends in catch composition, catch per unit effort (CPUE), and species abundance.

### **5.3.6. Estimation of annual Gross Value of Production (GVP) of SPS in Lake Albert**

The GVP of fresh fish for each species determined at the beach level was calculated by multiplying the average price per kilogram of fresh fish of the species by the total catch weight in the year (Equation 6).

$$GVP = C_{s,y} \cdot \bar{P}_{vg,s,y} \quad (10)$$

Where  $\bar{P}_{vg,s,y}$  is the species mean price for vessel gear  $vg$ , during year  $y$ .

Results of annual catches and gross value of production from this study were compared with those reported in previous studies (NaFIRRI, 2021a) to identify temporal trends.

### **5.4. Statistical analysis of catch rates**

To assess spatial variation in SPS catch rates, a two-way Analysis of Variance (ANOVA) was conducted to determine whether mean catch per unit effort (CPUE) differed significantly among the sampled regions. Where significant differences were detected, a post-hoc Tukey's Honestly Significant Difference (HSD) test was applied to identify specific pairwise regional differences. To evaluate temporal variation, a two-way ANOVA was used to examine the effects of sampling month and year on CPUE. This allowed for the assessment of both individual and interactive effects of temporal factors on catch rates. Independent sample  $t$ -tests were performed to compare mean CPUE for each target species (*E. bredoi* and *B. nurse*) between different vessel propulsion types (i.e., outboard engines versus paddles).

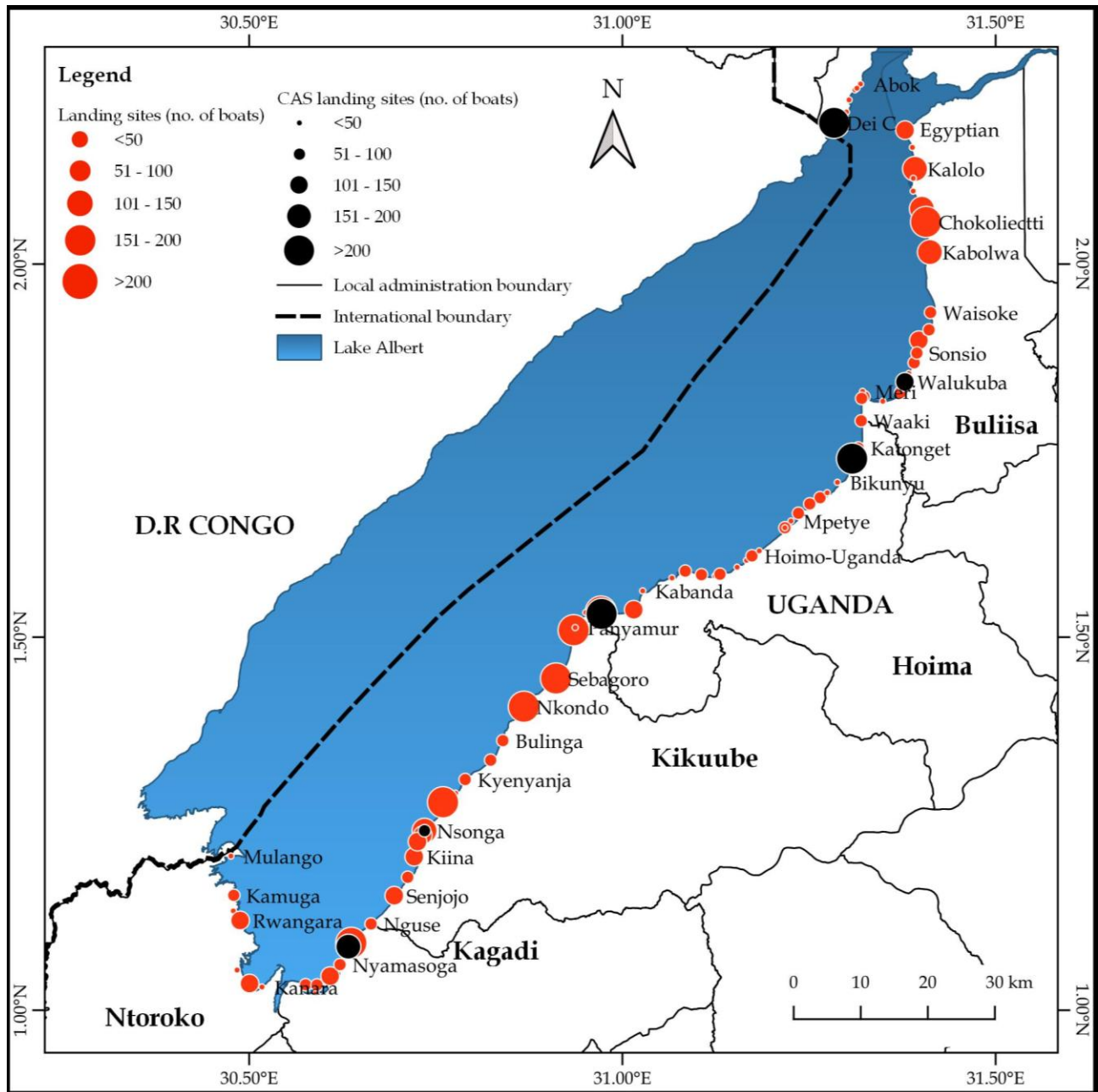
All statistical analyses were conducted using R version 4.3.2 (R Core Team, 2023). Spatial analyses, including the development of effort distribution maps and survey transects, were performed using QGIS version 3.12 (QGIS Development Team, 2018).

## **5.5. RESULTS**

### **5.5.1. Spatial distribution of light-based fishing effort across landing sites on Lake Albert.**

Analysis of 2021 Frame Survey data identified 78 landing sites along the Ugandan shoreline of Lake Albert (Figure 5.5-1), all of which supported light fishing activities, primarily targeting the small pelagic species *E. bredoi* and *B. nurse*. Of the 9760 fishing boats recorded lake-wide,

approximately 40% (3904 boats) were engaged in light-based fishing for SPS. Fishing effort exhibited a geographically skewed distribution, with the central region harbouring the highest concentration (Figure 5.5-1). Specifically, the central region accounted for 46.6% of landing sites, followed by the northern (32.9%) and southern (20.5%) regions. This pattern was also reflected in the distribution of fishing boats, with 52% (5,075 boats) located in the central region, compared to 24.7% in the north and 23.3% in the south. Similarly, of the 14,000 fishers recorded in 2021, 58% operated in the central region, while the northern and southern regions accounted for 24% and 18%, respectively.



**Figure 5.5-1.** Geospatial distribution of fishing effort along the Ugandan shoreline of Lake Albert based on the 2021 Frame Survey. Red circles indicate the number of boats per landing site. Black circles denote Catch Assessment Survey (CAS) landing sites used for monthly data collection in this study.

### 5.5.2. Temporal variation in light-based small-pelagic species catch, effort, and GVP (2007–2022).

Annual catch data from 2007 to 2022 revealed consistently higher landings of *Engraulicypris bredoi* compared to *Brycinus nurse* in the Ugandan waters of Lake Albert (Table 5.5-1). The catch of *E. bredoi* rose sharply from 34,665 tonnes in 2007 to a peak of 154,463 tonnes in 2020, before declining moderately to 74,060 tonnes by 2022 (Table 5.5-1). In contrast, catches of *B. nurse* declined steadily over the same period, falling from 116,702 tonnes in 2007 to 28,002 tonnes in 2022 (Table 5.5-1). Gross Value of Production (GVP) followed a similar trajectory to the catch trends, increasing from USD 35.16 billion in 2007 to a peak of USD 299.8 billion in 2020, largely driven by a surge in *E. bredoi* landings. This was followed by a further decline to USD 161.4 billion in 2022, coinciding with a reduction in catch and a contraction in fishing effort (Table 5.5-1). Fishing effort, measured by the number of boats targeting small-pelagic species (SPS), increased steadily from 1,619 in 2007 to a peak of 3,200 in 2019–2020. However, a sharp reduction occurred in 2021, with active SPS fishing boats declining by 41.7% to 1,867 (Table 5.5-1).

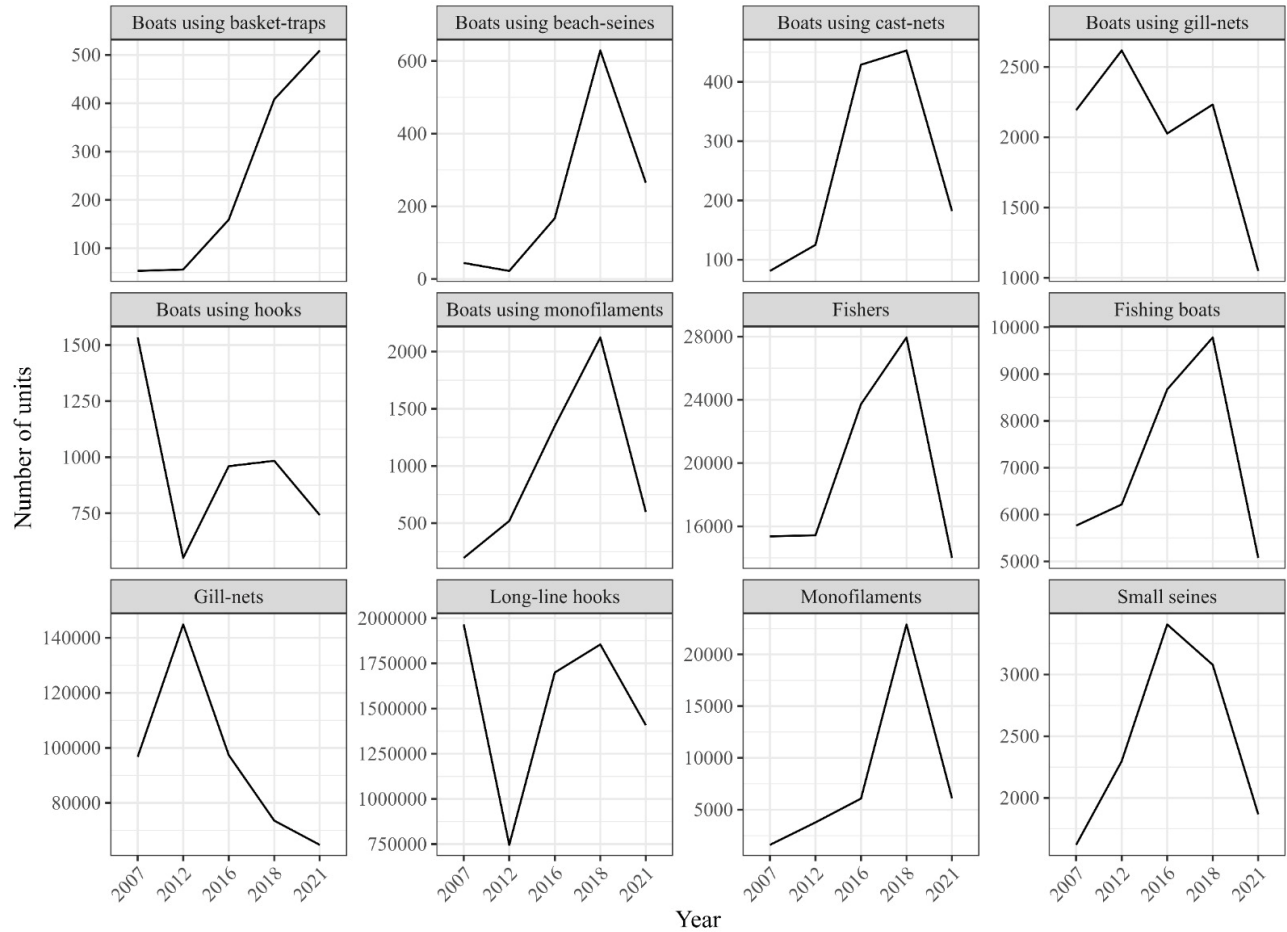
Table 5.5-1. Temporal trends in catch (tonnes), fishing effort (number of boats), and Gross Value of Production (USD billions) for *Engraulicypris bredoi* and *Brycinus nurse* in the Ugandan waters of Lake Albert from 2007 to 2022. Source: national reports (Mbabazi et al., 2012; NaFIRRI, 2007; Nakiyende et al., 2023b), and estimates from current. Exchange rates were derived from Bank of Uganda.

Period	Effort	Catch (tonnes)			Gross Value of Production	Source of Data
Year	No. of Boats	<i>E. bredoi</i>	<i>B. nurse</i>	Total	GVP (USD)	
2007	1,619	34,665	116,702	151,367	35,160	NaFIRRI, 2007
2012	2,303	78,042	50,905	128,947	47,862	Mbabazi et al, 2012
2013	2,673	101,048	31,832	132,880	95,568	NaFIRRI, 2014
2014	3,043	34,096	13,795	47,891	26,066	NaFIRRI, 2014
2019	3,200	121,106	67,332	188,437	198,280	NaFIRRI, 2019
2019	3,200	97,699	28,780	126,479	160,279	Current study
2020	3,200	154,463	92,181	246,644	229,777	NaFIRRI, 2021a
2020	3,200	129,540	31,195	160,735	207,644	Current study
2021	1,867	84,158	49,589	133,747	189,397	Current study
2022	1,867	74,060	28,002	102,062	161,398	Current study

The presence of two datasets for 2019 and 2020 reflects differences in data sources and estimation approaches, as clarified in the final column of Table 5.5-1. The first estimates are derived from NaFIRRI national fisheries statistical reports, which are based on conventional Catch Assessment Survey (CAS) procedures without explicit consideration of lunar periodicity. The second estimates are generated from the current study, which incorporated lunar phase effects into catch estimation. Presenting both datasets illustrate how methodological differences, particularly the inclusion or exclusion of lunar cycles, can influence catch and production estimates, thereby highlighting variability between standard reporting approaches and refined analytical methods.

### **5.5.3. Temporal trends in fishing effort indicators on Lake Albert**

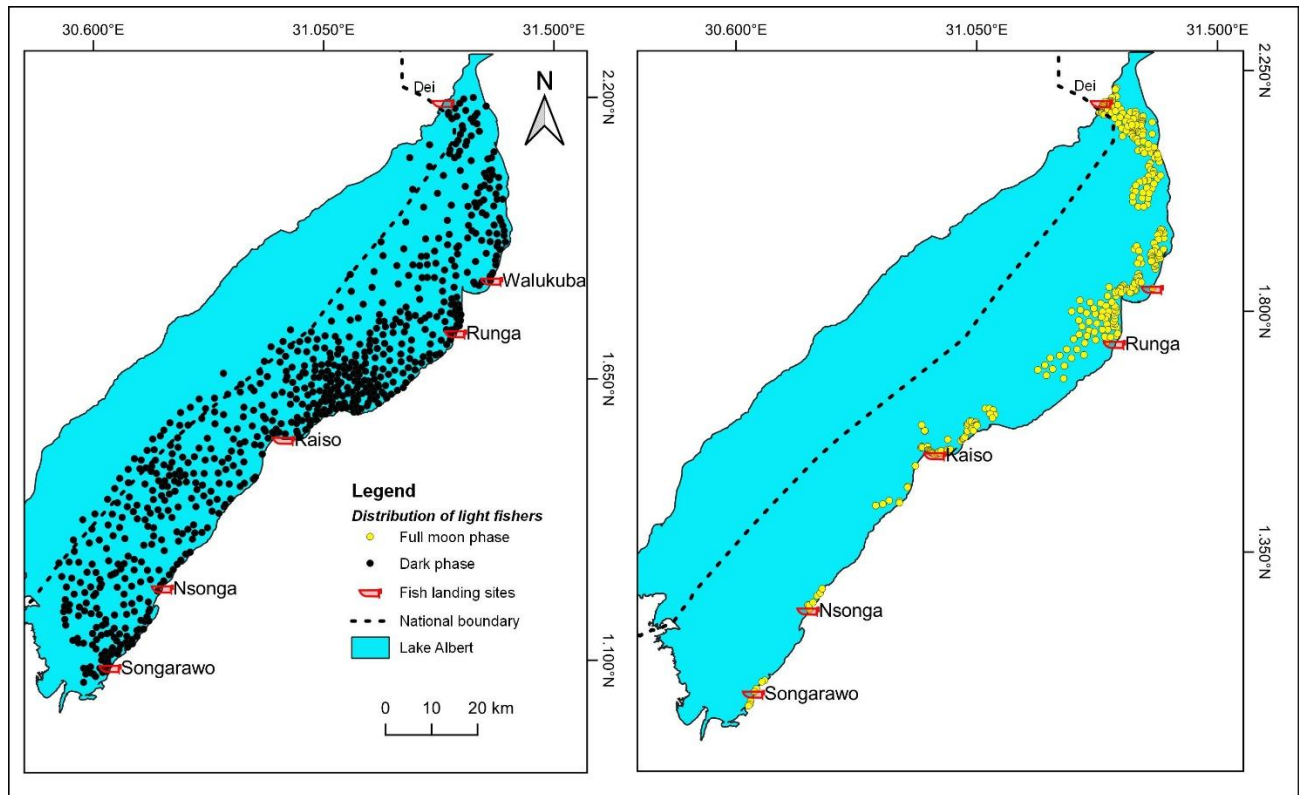
Figure 5.5-2 illustrates temporal changes in key fishing effort indicators on the Ugandan side of Lake Albert between 2007 and 2021, namely the number of fishing boats, gears used, and fishers. A general increase was observed across most indicators between 2007 and 2018, followed by a notable decline in 2021 (Figure 5.5-2). Specifically, the number of fishing boats, fishers, and small seine nets rose sharply up to 2018, then declined significantly by 2021. Basket traps showed a steady increase throughout the entire period. In contrast, the use of gillnets and associated boats increased modestly from 2007 to 2012, then declined gradually through 2021. Longline hooks and their associated boats exhibited a unique pattern: initially declining sharply between 2007 and 2012, rebounding in 2016, and stabilizing thereafter. Similar trends were observed for monofilaments and beach seines, which peaked in 2018 before decreasing in the 2021 survey.



**Figure 5.5-2.** Temporal trends in key fishing effort indicators on the Ugandan side of Lake Albert from 2007 to 2021. Sourced from national Frame Survey reports from 2007 – 2021 (NaFIRRI, 2021b).

#### 5.5.4. Spatial-temporal distribution of fishing lights during new and full-moon phases.

The spatial and temporal distribution of fishing lights exhibited clear distinctions between new (dark) and full (bright) moon phases (Figure 5.5-3). Fishing activity indicated by the presence of fishing lights, was substantially higher during the new moon, averaging eight boats per square kilometre, compared to three boats per square kilometre during the full moon. During the full moon, fishing lights were predominantly concentrated in shallow inshore areas near the shoreline. In contrast, during the new moon, fishing lights were more broadly and evenly distributed across the lake, including deeper offshore zones. Notably, the spatial extent of fishing lights encompassed the entire Uganda portion of Lake Albert, with some lights detected beyond the international boundary into the Democratic Republic of the Congo (DRC), where light fishing is prohibited.



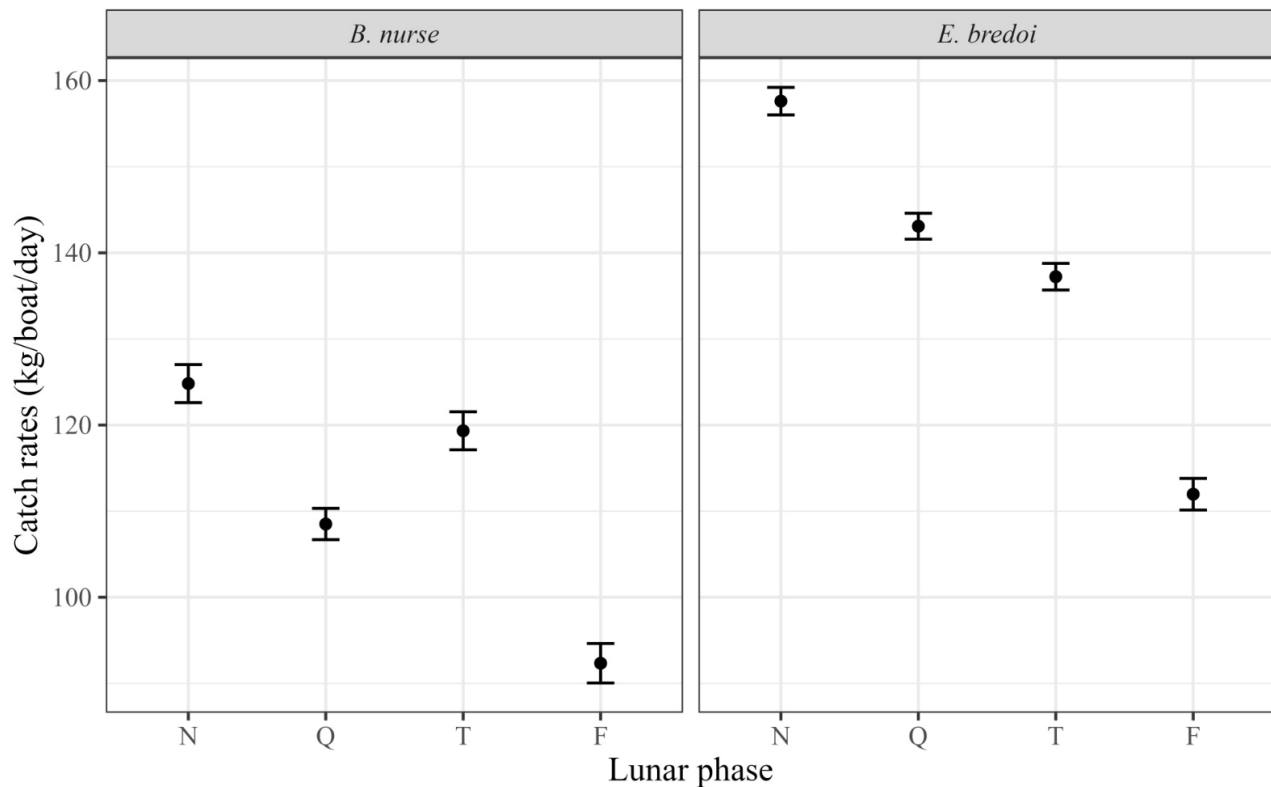
**Figure 5.5-3.** Spatial-temporal distribution of fishing lights in the Ugandan waters of Lake Albert during the dark (black) and full (yellow) moon phases. Data were acquired in September 2020.

### 5.5.5. Catch Rates (kg/boat/day) of target species across lunar phases.

The analysis of catch rates across lunar phases revealed a distinct and statistically significant influence of moonlight on the catchability of both *Brycinus nurse* and *Engraulicypris bredoi* (Figure 5.5-4). For *B. nurse*, the mean catch rate was highest during the New Moon ( $124.82 \pm 2.21$  kg/boat/day) and lowest during the Full Moon ( $92.34 \pm 2.30$  kg/boat/day). Catch rates showed a consistent decline from the New Moon through the First and Third Quarter phases, indicating a strong negative correlation with increasing moonlight.

A similar pattern was observed for *E. bredoi*, with the highest mean catch rate during the New Moon ( $157.61 \pm 1.60$  kg/boat/day) and the lowest during the Full Moon ( $111.97 \pm 1.84$  kg/boat/day). A two-way ANOVA confirmed that lunar phase had a highly significant effect on catch rates for both species ( $p < 0.001$ ). Post-hoc comparisons further revealed that the differences between New Moon and Full Moon catch rates were highly significant for both *B. nurse* and *E. bredoi* ( $p < 0.001$ ).

Additionally, *E. bredoi* consistently exhibited significantly higher catch rates than *B. nurse* across all lunar phases ( $p < 0.001$ ).

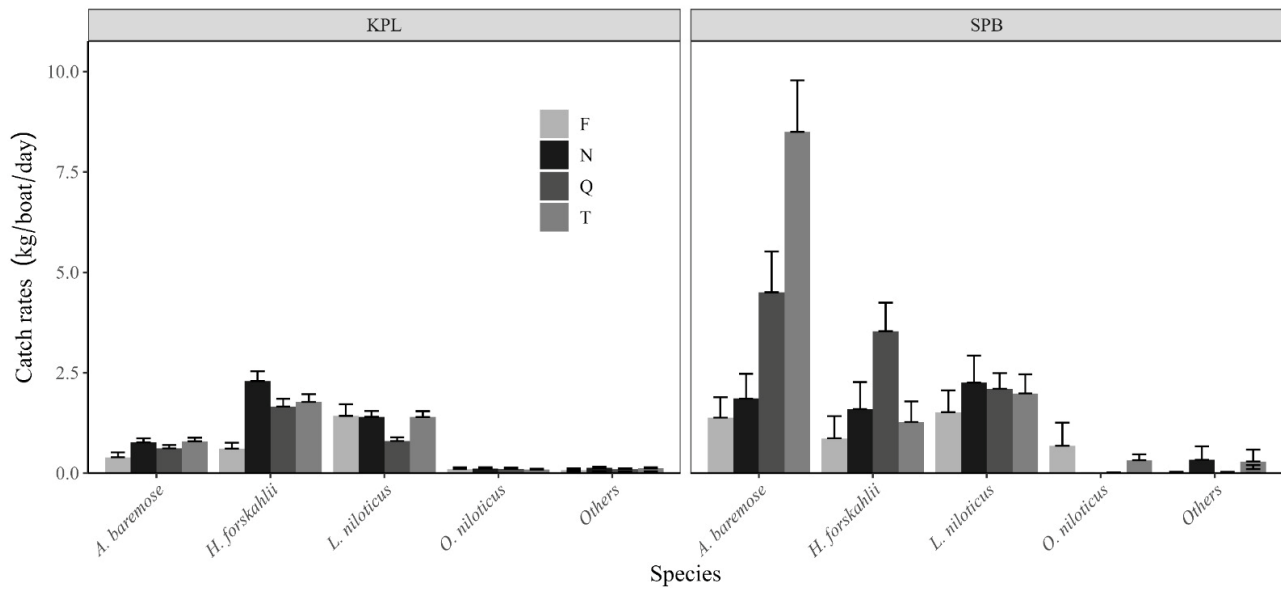


**Figure 5.5-4.** Variation of catch rates (kg/boat/day) for *B. nurse* and *E. bredoi* across lunar phases. Error bars represent the standard error. N = New moon, Q = First quarter, F = Full moon, T = Third quarter.

### 5.5.6. Mean catch rates (kg/boat/day) of common bycatch species in SPS catches across lunar phases.

The mean catch-per-unit-effort (CPUE) of common bycatch species recorded with SPS fishing operations varied considerably across lunar phases and light types (Figure 5.5-5). Generally, lower catch rates were observed during the full moon phase; however, species- and light-source-specific exceptions occurred. For example, *Lates niloticus* caught using kerosene pressure lamps (KPL) recorded its lowest mean catch rates during the first quarter moon phase ( $0.80 \pm 0.09$  kg/boat/day). In contrast, *A. baremoze* exhibited peak catch rates during the third quarter moon, with  $0.79 \pm 0.09$  kg/boat/day under KPL and a significantly higher CPUE of  $8.50 \pm 1.28$  kg/boat/day under solar-powered bulbs (SPB). *Hydrocynus forskahlii* showed the highest catch rates during the first

quarter moon when using SPB ( $3.53 \pm 0.71$  kg/boat/day), and during the new moon when using KPL ( $2.29 \pm 0.25$  kg/boat/day).



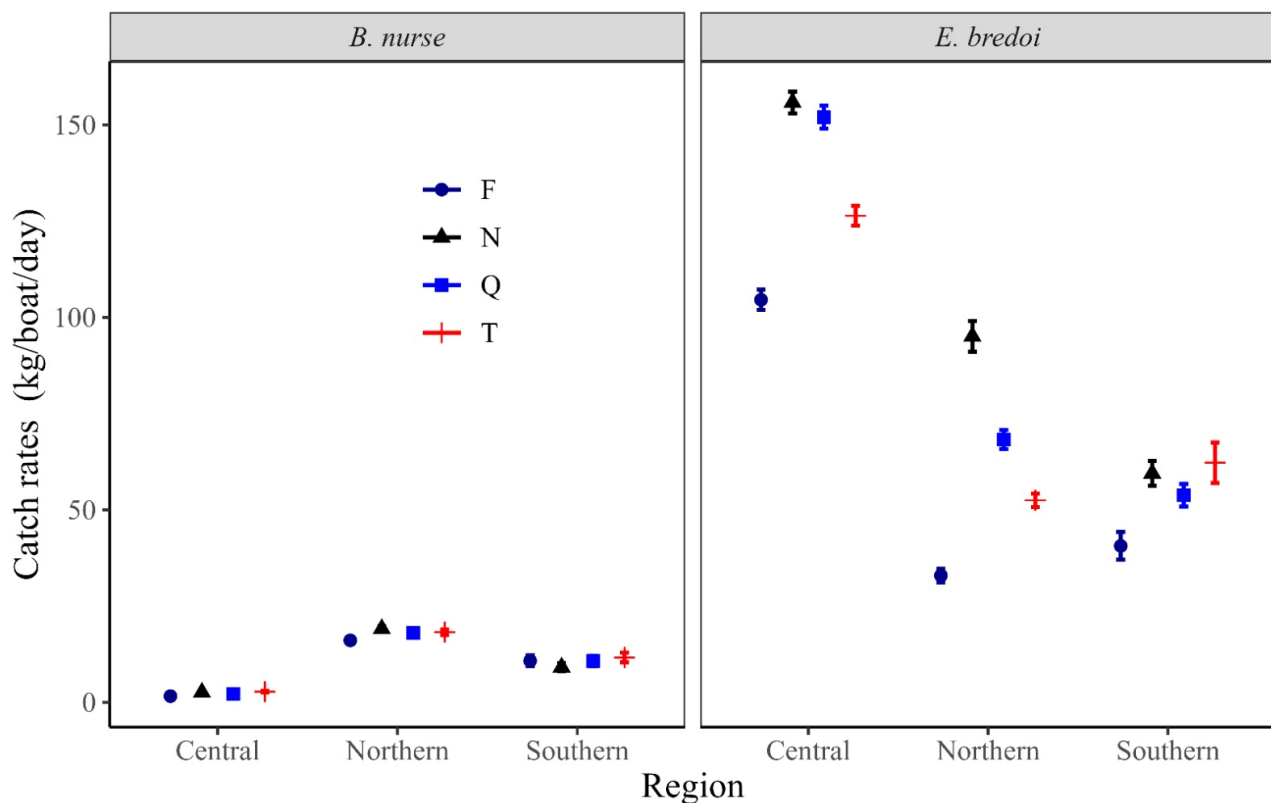
**Figure 5.5-5.** Mean catch rates (kg/boat/day  $\pm$  SE) of common bycatch species associated with SPS fishing operations on Lake Albert, Uganda, across lunar phases and light types (KPL = kerosene pressure lamps; SPB = solar-powered bulbs). The “Others” category comprises *Bagrus bajad*, *Barbus bynnii*, *Clarias gariepinus*, *Citharinus niloticus*, *Distichodus niloticus*, *Malapterurus electricus*, *Polypterus senegalis*, *Mormyrus* spp., *Labeo* spp., *Schilbe* spp., and Haplochromines.

### 5.5.7. Spatial and lunar variations in catch rates (kg/boat/day) of *Brycinus nurse* and *Engraulicypris bredoi*.

Catch rates of both *B. nurse* and *E. bredoi* were significantly influenced by moon phase and region (Figure 5.5-6). For *B. nurse*, the effect of moon phase was statistically significant ( $F = 3.51$ ,  $p < 0.05$ ), although less pronounced than the regional effect ( $F = 1020.67$ ,  $p < 0.0001$ ). There was no significant interaction between moon phase and region ( $F = 1.58$ ,  $p > 0.05$ ). Post-hoc analysis revealed that catch rates for *B. nurse* were significantly higher during the New Moon and Third Quarter phases compared to the Full Moon (mean difference = 1.59 kg/boat/day,  $p < 0.05$ ). Although catch rates during the First Quarter were also higher than those of the Full Moon, the difference was not statistically significant ( $p > 0.05$ ). No other lunar phase pairwise comparisons showed significant differences ( $p > 0.05$ ). However, all regional pairwise comparisons were statistically significant ( $p <$

0.001), with the Northern region consistently recording the highest catch rates, followed by the Southern and Central regions.

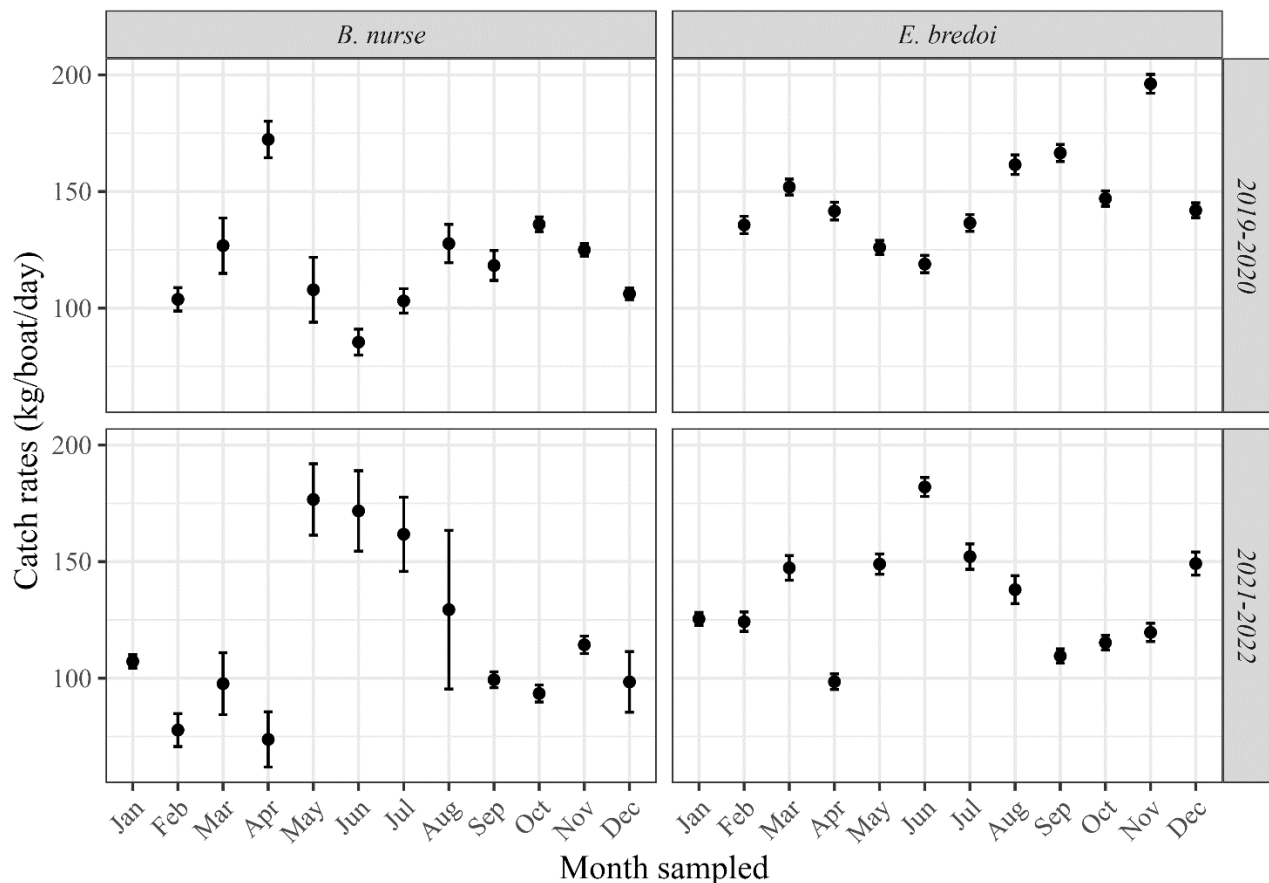
For *E. bredoi*, catch rates were significantly influenced by moon phase ( $F = 110.38$ ,  $p < 0.0001$ ), region ( $F = 767.65$ ,  $p < 0.0001$ ), and their interaction ( $F = 7.54$ ,  $p < 0.0001$ ). Post-hoc tests revealed region-specific lunar effects. In the Northern region, catch rates during the New Moon were significantly higher than during the Full Moon ( $P < 0.0001$ ). In contrast, this difference was not significant in the Southern region ( $P > 0.05$ ). Further analysis showed that during the Full Moon and Third Quarter phases, catch rates in the Northern region were significantly lower than those in the Central region ( $P < 0.0001$ ). Notably, catch rates during the New Moon were higher in the Central region than during the Full Moon, but the opposite was observed in the Northern region (Figure 5.5-6).



**Figure 5.5-6.** Mean catch rates (kg/boat/day  $\pm$  SE) of *Engraulicypris bredoi* and *Brycinus nurse* across regions of the Ugandan side of Lake Albert, categorized by moon phase. Moon phases are abbreviated as follows: F = Full moon, N = New moon, Q = First Quarter moon, and T = Third Quarter moon.

**5.5.8. Temporal variability in catch rates of *Engraulicypris bredoi* and *Brycinus nurse* across months.**

Monthly catch rates (kg/boat/day) of *E. bredoi* and *B. nurse* exhibited clear seasonal fluctuations across both sampling periods (2019–2020 and 2021–2022), as shown in Figure 5.5-7. Catch rates of both varied significantly across months in both years ( $p < 0.05$ ), with pronounced declines observed between March and June of 2019–2020, and between June and October for the 2021/2022 period (Figure 5.5-7). However, mean annual catch rates did not differ between the two years (*B. nurse*:  $F = 1.6387$ ,  $DF = 1$ ,  $p > 0.05$ ; *E. bredoi*:  $F = 0.2417$ ,  $DF = 1$ ,  $p > 0.05$ ).

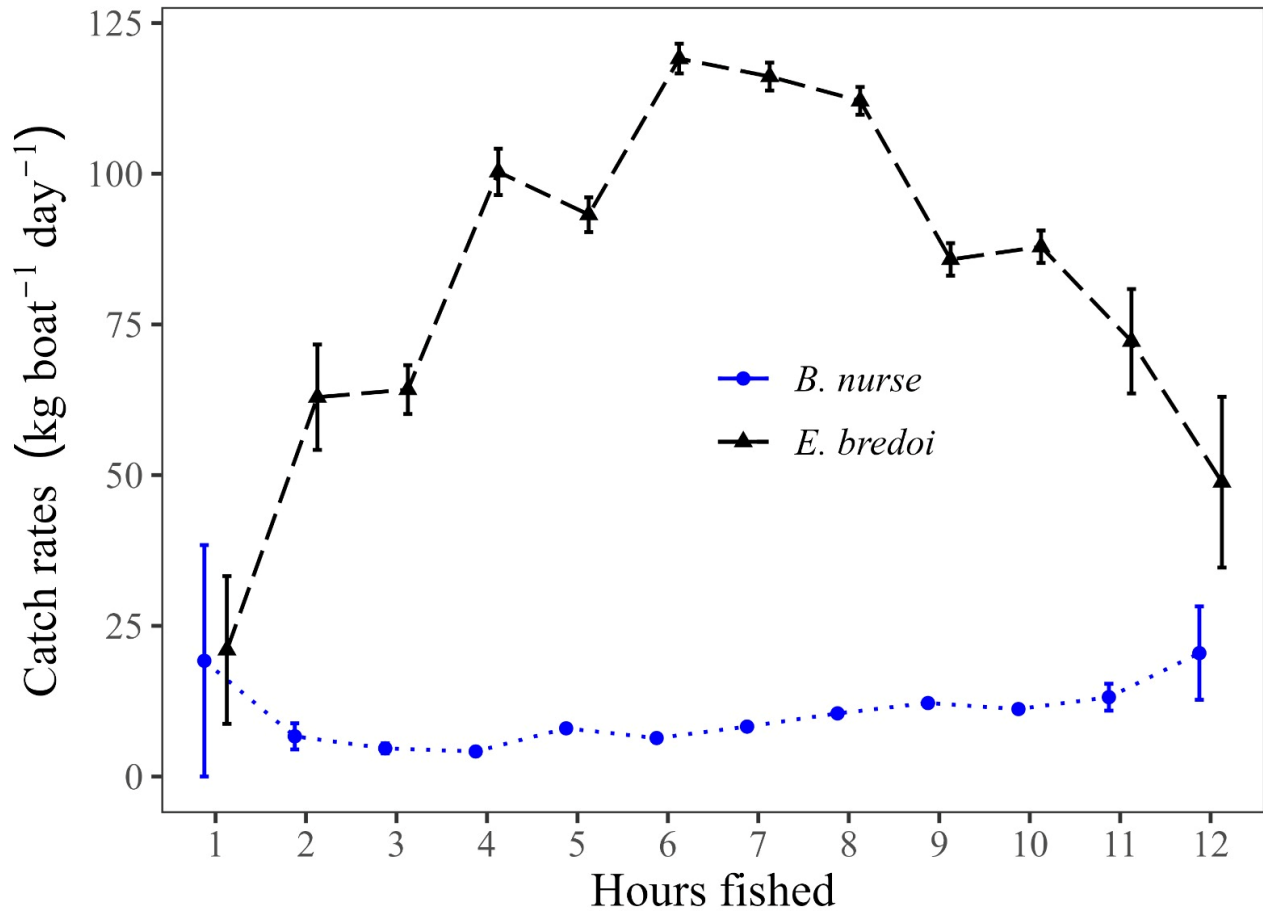


**Figure 5.5-7.** Monthly variation in mean catch rates (kg/boat/day  $\pm$ SE) of *Engraulicypris bredoi* and *Brycinus nurse* on the Ugandan side of Lake Albert for the 2019/2020 and 2021/2022 sampling periods.

### **5.5.9. Influence of fishing duration on catch rates of *Engraulicypris bredoi* and *Brycinus nurse*.**

Fishing duration had a pronounced and species-specific influence on catch-per-unit-effort (CPUE) for both *E. bredoi* and *B. nurse* (Figure 5.5-8). For *E. bredoi*, catch rates increased sharply with longer fishing durations, peaking between 6 to 8 hours at approximately 115 kg/boat/day. Beyond 8 hours, a gradual decline in CPUE was observed, although catch rates remained relatively high until the 10th hour before declining more steeply toward the 12th hour.

In contrast, *B. nurse* exhibited relatively low and stable catch rates across most fishing durations, with no clear peak. CPUE values ranged between 5–15 kg/boat/day for durations from 2 to 11 hours, indicating a weak relationship between fishing duration and catch rate. However, slightly elevated catch rates were recorded at 1 and 12 hours, though variability was high, as shown by larger error bars. Statistical analysis confirmed a significant effect of fishing duration on CPUE for *E. bredoi* (DF = 11, F = 19.936,  $p < 0.001$ ), whereas *B. nurse* showed no statistically significant variation across hours fished (DF = 11, F = 17.572,  $p > 0.05$ ).



**Figure 5.5-8.** Variation in mean catch rates (kg/boat/day  $\pm$ SE) of *Engraulicypris bredoi* (black triangles, dashed line) and *Brycinus nurse* (blue circles, dotted line) in relation to hours fished per night on Lake Albert, Uganda.

#### 5.5.10. Variation in mean catch rates (kg/boat/day) by vessel propulsion mode

Mean catch rates of *Engraulicypris bredoi* and *Brycinus nurse* varied significantly with vessel propulsion mode (Table 5.5-2). For *E. bredoi*, outboard-powered boats recorded a significantly higher mean catch rate ( $172.2 \pm 1.4$  kg/boat/day) compared to paddle-powered boats ( $108.8 \pm 3.05$  kg/boat/day;  $t = 18.84$ ,  $DF = 1289.6$ ,  $p < 0.001$ ). A similar trend was observed for *B. nurse*, with outboard-powered boats yielding  $109.45 \pm 1.2$  kg/boat/day compared to  $77.6 \pm 9.1$  kg/boat/day for paddle-powered vessels ( $t = 3.47$ ,  $DF = 212.1$ ,  $p < 0.001$ ).

Table 5.5-2. Mean catch-per-unit-effort (kg/boat/day) for *E. bredoi* and *B. nurse*, disaggregated by vessel propulsion mode. Statistical comparisons were made using Welch's *t*-test to account for unequal variances.

Species	Propulsion Mode	Mean Catch Rate (kg/boat/day) ± SE	t-value	DF	p-value
<i>Engraulicypris bredoi</i>	Outboard Engine	172.2 ± 1.4	18.837	1290	<0.001
<i>Engraulicypris bredoi</i>	Paddle-powered	108.8 ± 3.05			
<i>Brycinus nurse</i>	Outboard Engine	109.45 ± 1.2	3.47	212.1	0.0006
<i>Brycinus nurse</i>	Paddle-powered	77.6 ± 9.1			

### 5.5.11. Species spatial abundance and distribution (acoustic biological backscatter) across lake regions).

The total mean biological backscatter (abundance) across all surveyed regions, expressed as the Nautical Area Scattering Coefficient (NASC), was estimated at 4664 m<sup>2</sup>·n.mi<sup>-2</sup>. Among the three lake regions, the Southern region recorded the highest abundance, while the Northern region had the lowest (Table 5.5-3). Small pelagics accounted for the majority of the total biological backscatter, with a mean NASC of 3822 m<sup>2</sup>·n.mi<sup>-2</sup>, representing approximately 81.9% of the total. The South Coastal stratum contributed the highest share of this abundance at 1068 m<sup>2</sup>·n.mi<sup>-2</sup> (22.9%), followed by the Central Deep stratum with 584.8 m<sup>2</sup>·n.mi<sup>-2</sup> (12.5%), while the South Inshore had the lowest at 83.2 m<sup>2</sup>·n.mi<sup>-2</sup> (1.8%).

Single targets (indicative of larger-bodied fish) contributed 842.3 m<sup>2</sup>·n.mi<sup>-2</sup>, accounting for 18.1% of the total backscatter. Again, the South Coastal stratum recorded the highest abundance of single target (395.17 m<sup>2</sup>·n.mi<sup>-2</sup>; 8.5%), while the South Inshore had the lowest (16.52 m<sup>2</sup>·n.mi<sup>-2</sup>; 0.4%) (Table 5.5-3). Overall, deeper strata tended to support higher fish abundance, except in the southern region, where the coastal exhibited greater abundance than the adjacent inshore zone.

**Table 5.5-3.** Mean Nautical Area Scattering Coefficient (NASC ± SE) across lake strata, estimated from hydroacoustic backscatter data collected in Lake Albert, Uganda, in September 2021. Estimates are presented for: (i) all scatter (total backscatter), (ii) large-bodied fish (single targets), and (iii) small pelagic species (SPS) based on echo integration.

Region/Stratum	Total Backscatter				Single Targets				Small Pelagic Species			
	Mean	Low	Upper	n	Mean	Low	Upper	n	Mean	Low	Upper	n
Central Coastal	665.7	532.7	811.7	161	131.3	89.1	185.2	144	566.1	454.1	691.9	144

Central Deep	748.7	622.9	877.6	183	111.5	89.6	135.8	179	584.8	494.7	682.7	179
Central Inshore	236.2	142.0	355.0	27	61.4	13.7	148.1	18	227.4	116.6	380.1	18
North Coastal	212.8	176.1	250.1	50	27.5	19.0	36.6	44	191.2	157.8	226.31	44
North Deep	438.3	317.6	589.6	61	64.6	43.6	91.0	60	354.4	255.7	481.0	60
North Inshore	243.5	195.0	297.3	75	73.1	46.8	116.6	66	166.7	141.6	194.1	66
South Coastal	1417	1081.4	1804.4	116	283.8	201.8	376.3	112	1068.0	831.1	1337.7	112
South Deep	628.9	362.9	999.7	27	77.1	20.6	174.3	24	579.6	354.1	857.3	24
South Inshore	72.7	58.6	87.7	76	11.9	6.7	18.0	38	83.2	63.3	104.9	38
<b>Subtotal</b>	<b>4664</b>	<b>3489.1</b>	<b>6073</b>		<b>842.3</b>	<b>529.2</b>	<b>1263.1</b>		<b>3822</b>	<b>2868.9</b>	<b>4956.2</b>	

## 5.6. DISCUSSION

### 5.6.1. Spatial-temporal dynamics of light-based SPS fisheries on Lake Albert.

The Lake Albert fishery supports a diverse assemblage of both selective and non-selective fishing gears targeting a range of species, including small-bodied pelagic and large-bodied fishes (Mbabazi et al., 2012; Nakiyende et al., 2013; 2023a; 2023b). The SPS fishery, dominated by *E. bredoi* and *B. nurse*, primarily relies on artificial light attraction in combination with small seine (Lampara) nets, a method widely applied across AGLs including Victoria, Malawi, and Tanganyika (Kolding et al., 2019; Mgana et al., 2019; LVFO, 2020; Wandera, 1990). Similar reliance on light-based pelagic fisheries is also seen globally, in systems as diverse as Southeast Asian reservoirs, Mediterranean sardine fisheries, and South American anchoveta fisheries, underscoring the growing economic dependence on these highly productive but environmentally sensitive resources (Ben-Yami, 1976; Marchesan et al., 2005).

Since 2007, fishing effort on Lake Albert has markedly increased, evidenced by a rise in the number of fishing boats, gear units, and fishers, with a notable but temporary decline between 2018 and 2021 following heightened enforcement by the Fisheries Protection Unit (FPU) (NaFIRRI, 2021b). This expansion coincided with a shift in target species from large-bodied fishes such as *L. niloticus*, *H. forskahlii*, *A. baremoze*, and *Oreochromis* spp. to small pelagic species, mirroring broader regional trends where SPS have become increasingly dominant in artisanal and commercial fisheries (Kolding et al., 2019; Mangeni-Sande et al., 2019; LVFO, 2022). Comparable transitions have been reported in other inland and coastal systems globally, where overfishing of large-bodied taxa has been followed by increasing reliance on small, fast-reproducing pelagic species (Allan et al.,

2005; FAO, 2022). This shift highlights both the ecological resilience and the vulnerability of SPS-dominated fisheries, particularly where management institutions remain weak.

Spatially, the concentration of light-based SPS fishing effort and catches in the central regions of Lake Albert likely reflects ecological suitability, combined with proximity to infrastructure and markets such as Hoima. Variability in CPUE across regions could reflect underlying environmental heterogeneity (Hamilton et al., 2022). The shallower, vegetated northern and southern areas appeared preferential for *B. nurse*, while deeper central areas supported higher abundance of *E. bredoi*, consistent with catch records (Mbabazi et al., 2012; Nakiyende et al., 2023b). These species-specific spatial niches mirror observations from Lake Tanganyika, Lake Victoria, and other tropical lakes where depth and habitat structure influence pelagic distributions and catchability (Mulimbwa et al., 2014; Mgana et al., 2019).

Catch rate patterns across fishing duration highlight species-specific behavioural responses to light attraction. For *E. bredoi*, catch rates rose sharply to peak after 6–8 hours of illumination before declining, suggesting a relatively narrow optimal harvest window, possibly due to light saturation or avoidance behaviour. *B. nurse*, by contrast, maintained lower but steadier catch rates across the fishing night, indicative of weaker phototaxis or greater avoidance of illuminated zones. These dynamics, observed in other SPS such as *Stolothrissa tanganyicae* and *Rastrineobola argentea*, emphasize the need to align fishing schedules with behavioural ecology to optimize effort and minimize waste (Wandera & Balirwa, 2010; Mgana et al., 2019).

### **5.6.2. Influence of lunar cycles on light-based SPS fisheries**

Fishing activity and catch rates for *E. bredoi* and *B. nurse* peaked during dark moon phases, when low ambient light enhanced the effectiveness of artificial illumination (Bassi et al., 2022; Czarnecka et al., 2019). Conversely, full moon periods reduced catch rates and shifted effort toward inshore areas, consistent with classical observations of phototactic schooling fishes (Blaxter & Parrish, 1965; Pavlov & Kasumyan, 2000). Similar lunar effects have been documented in pelagic fisheries globally—from sardines in the Mediterranean to anchovies in Southeast Asia—where moonlight modulates catchability, fishing effort, and fleet dynamics (Marchesan et al., 2005; Lowry et al., 2007; Poisson et al., 2010).

The higher CPUE of *E. bredoi* during dark phases suggests greater vulnerability or catchability relative to *B. nurse*. Such lunar-driven catchability cycles have management implications beyond Lake Albert. In several global small pelagic fisheries, effort adjustments aligned with lunar phases have been used to create de facto fishing refuges and stabilize catch fluctuations (Pulver, 2017; Andrzejaczek et al., 2024). For Lake Albert, this presents an opportunity to apply biologically informed temporal management, such as instituting fishing holidays during full moon phases when catchability is low and economic returns are marginal.

### **5.6.3. Acoustic insights and multi-species dynamics**

Hydroacoustic surveys confirmed the dominance of SPS, which comprised ~80% of total biological backscatter (NASC), consistent with artisanal catch data where *E. bredoi* and *B. nurse* contribute ~70% of annual landings (Mbabazi et al., 2012; 2019; Nakiyende et al., 2013, 2023a; 2023b). The remaining acoustic signal is plausibly linked to large-bodied species (*L. niloticus*, *A. baremoze*, *H. forskahlii*, *Oreochromis* spp.), which persist in the fishery but at reduced levels. Comparable acoustic dominance of SPS has been reported in other AGLs and in marine upwelling systems (e.g., Peruvian anchoveta), reinforcing their ecological centrality in energy transfer and food web support (Kolding et al., 2019; FAO, 2022). The lack of species-specific target strength data, however, constrains biomass precision—a limitation echoed in regional acoustic monitoring programs (Mgana et al., 2019). Addressing this knowledge gap through coordinated research would improve accuracy of stock assessments across AGLs and similar pelagic systems globally.

### **5.6.4. Management implications and transboundary coordination**

Findings underscore the urgent need for adaptive management of Lake Albert's SPS fishery, particularly given its transboundary nature and shared resource base with the Democratic Republic of Congo (DRC). Regional experiences from Lakes Victoria and Tanganyika demonstrate that uncoordinated exploitation of highly mobile pelagic stocks can accelerate resource depletion and fuel cross-border conflicts (LVFO, 2020; Mulimbwa et al., 2014). Coordinated regulations between Uganda and DRC—such as joint lunar-based effort controls restricting light fishing to dark moon periods (approximately 21 nights per month)—could reduce pressure while delivering cost savings to fishers. Similar low-cost, calendar-based management strategies have been employed in Asian and

South American small pelagic fisheries, yielding both ecological and socio-economic benefits (Das et al., 2015; FAO, 2022).

The significant interaction between lunar phase and fishing region for *E. bredoi* highlights the influence of local limnology and behavioural plasticity on catch dynamics (Libini & Khan, 2012; Nirmal et al., 2017). Such complexity is not unique to Lake Albert; in Lake Tanganyika and Lake Malawi, upwelling, diel vertical migration, and lunar cycles jointly shape SPS distribution and catchability (Mulimbwa et al., 2014; Mgana et al., 2019). Globally, similar spatiotemporal interactions have necessitated regionally nuanced, behaviourally informed strategies that couple gear regulation, effort limitation, and seasonal or lunar-based closures. For Lake Albert, embedding such approaches in transboundary frameworks would strengthen resilience, align with international best practice, and secure the long-term viability of its SPS-dominated fishery.

#### **5.6.5. Broader management implications**

The findings from Lake Albert's light-based SPS fishery highlight management challenges and opportunities that extend well beyond this single system. Light-based fisheries targeting SPS are common across tropical inland waters such as Lakes Victoria, Tanganyika, Malawi, Kivu, and Turkana (Kolding et al., 2019, Mgana, 2019), as well as in coastal marine systems, where lunar cycles strongly influence catchability and fisher behavior (Nightingale et al., 2006; Nhat et al., 2023). Understanding how lunar periodicity shapes spatial-temporal catch patterns is therefore critical for designing harvest regulations that balance efficiency with sustainability in data-limited contexts. For example, aligning effort regulation and seasonal closures with predictable lunar-driven fluctuations could simultaneously reduce overexploitation risks and sustain fisher profitability.

More broadly, these insights emphasize the importance of management frameworks that explicitly account for behavioral ecology and fisher responses to natural cycles (Wilén et al., 2002; Salas and Gaertner, 2004). This is particularly relevant in small-scale fisheries where monitoring capacity is limited, but adaptive and low-cost measures, such as lunar-based fishing calendars, targeted effort caps, or gear restrictions, can be practically implemented. The Lake Albert case study thus contributes to a growing body of evidence on how artisanal light-based SPS fisheries in tropical ecosystems can be managed sustainably. Lessons from Lake Albert also resonate with SPS fisheries

in Asia and South America, where sustainability hinges on integrating behavioral ecology, technological adoption, and socio-economic dependence into management frameworks (Pauly et al., 2005; Fréon et al., 2008; Eriksson et al., 2016).

## **5.7. Conclusion and Recommendations**

### **5.7.1. Conclusion**

This study demonstrates that lunar cycles strongly influence the spatial–temporal dynamics of the small pelagic species (SPS) fishery in Lake Albert. Catch rates and fishing effort peaked during dark moon phases and declined under full moon illumination, highlighting the critical role of lunar periodicity in shaping fishing success. Spatially, *Engraulicypris bredoi* dominated deeper central waters, while *Brycinus nurse* was more prevalent in shallow, vegetated northern and southern zones, reflecting habitat-specific distributions and fisher preferences linked to market access and operational feasibility.

These patterns align with observations from other African Great Lakes and tropical small pelagic fisheries globally, where lunar-driven catchability and habitat partitioning have profound implications for stock assessment and management. By integrating spatial, temporal, and behavioural dynamics into management frameworks, this study provides a robust, science-based foundation for adaptive, ecosystem-based approaches. Importantly, it also underscores the need for regional cooperation, particularly in transboundary systems like Lake Albert, to harmonize effort controls, optimize fishing calendars, and ensure the long-term sustainability of SPS, which are increasingly central to food security and livelihoods across Africa and other tropical inland fisheries.

### **5.7.2. Recommendations**

1. Adopt a lunar-based fishing calendar: Management measures to restrict SPS light-based fishing to dark moon phases and implement full-moon closures to reduce fishing pressure on SPS stocks and protect inshore critical habitats should be adopted. This would require revising the existing Fishing regulation in Uganda’s Fish (Fishing) Rules, 2010.
2. Integrate lunar phases into routine fisheries monitoring protocols such as Catch Assessment Surveys (CASs) to capture catch variability across lunar cycles, to improve the accuracy of stock assessments and management decisions.

3. Strengthen transboundary fisheries governance: Uganda should enhance collaboration with the Democratic Republic of the Congo (DRC) to harmonize fishing regulations, coordinate enforcement, and establish joint SPS management frameworks.
4. Advance hydroacoustic survey precision: Future research should incorporate species-specific target strength data into acoustic assessments to improve biomass estimation and strengthen fisheries monitoring capacity.
5. Implement long-term SPS monitoring: Support long-term monitoring research on SPS stocks to enable timely, adaptive management responses to ecological and fishery changes.

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## **CHAPTER SIX**

### **LIFE-HISTORY TRAITS OF ENGRAULICYPRIS BREDOI AND BRYCINUS NURSE IN LAKE ALBERT, UGANDA.**

#### **CONTEXT**

This chapter provides a biological health check of the target species by assessing key parameters such as size at maturity, growth patterns, and condition factors. The study finds that *E. bredoi* and *B. nurse* currently exhibit resilient population structures with positive allometric growth, indicating they are well-adapted to the current environmental conditions of Lake Albert. However, a critical vulnerability is noted for *B. nurse*, which is frequently captured at sizes smaller than its length at 50% maturity ( $L_{m50}$ ) due to the small mesh sizes used in light fishing. According to life-history theory, such sustained size-selective mortality could trigger long-term shifts in reproductive strategies, such as earlier maturation and stunted growth. To safeguard the long-term productivity of these stocks, the chapter emphasizes the need for gear-selectivity adjustments that align mesh sizes with the biological maturation schedules of the species.

The detailed chapter is presented as a publishable manuscript under the title “Life-history traits and population structure of Nurse tetra (*Brycinus nurse*) and *Engraulicypris bredoi* in Lake Albert. Implications for sustainable management.”

#### **ABSTRACT**

Understanding life-history traits of fishes is essential for effective fisheries management. This study determined the size at 50% maturity ( $L_{m50}$ ), length-weight relationship (LWR), condition factor (K), breeding pattern, and population size structure of *Brycinus nurse* and *Engraulicypris bredoi* in Lake Albert, Uganda. Data were collected through experimental fishing and examination of artisanal catches from February 2021 to June 2022.

Results showed differences in  $L_{m50}$  between species and sexes. *Brycinus nurse* females matured at a larger size (60.9 mm) than males (56.8 mm), while *E. bredoi* females matured at smaller size (23.9 mm) than males (31.6 mm). *Brycinus nurse* displayed a tri-modal size structure, while *E. bredoi*, maintained consistent size distribution throughout the year. Condition factor calculated for *B. nurse* and *E. bredoi* was 2.2 and 1.2, respectively, suggesting potential health and body shape

differences. Both species displayed positive allometric growth and year-round breeding, with seasonal variations. Breeding peaked in June for *E. bredoi* and between February and March for *B. nurse*. Artisanal catches (harvested using 5-mm mesh-size nets) revealed a notable prevalence of immature fish, with *B. nurse* and *E. bredoi* averaging 43.5 mm, and 29.8 mm Standard Length (SL) respectively, compared to 53 mm and 34.3 mm respectively in experimental catches (harvested using 8-mm mesh-size nets).

These results indicate an overall robust health of stocks of two species studied in Lake Albert. However, the presence of immature fish in artisanal catches raises concerns over gear size compliance, highlighting the necessity for strict enforcement of fishing regulations and regular monitoring of the fish populations to ensure sustainable management practices.

**Key words.** Artisanal fishery, breeding peak, fisheries management, sexual maturity, sustainable fishing.

## 6.1. INTRODUCTION

Understanding the life history traits of fishes is fundamental for effective fisheries management (Fryxell et al., 2015; Dang and Kienzler, 2019; Geffroy and Wedekind, 2020). These traits offer valuable insights into population dynamics and responses to fishing pressure and environmental changes (King and McFarlane, 2003; Chambers and Trippel, 2012; Cailliet, 2015; Lappalainen et al., 2016). Attributes such as size at maturity, condition, and breeding patterns play pivotal roles in shaping fish populations and management strategies (Sparre and Venema, 1998; Cadima, 2003; Haddon, 2011; Newman et al., 2016; Santos et al., 2021; 2022), aiding detection of fishery-induced changes in stock characteristics (Grabowska and Przybylski, 2015), and providing insight on how these populations respond to exploitation and environmental pressures (Sharpe and Hendry, 2009; Devine, 2012; Liang et al., 2014). In heavily exploited fish stocks, changes such as reduced size at maturity, reduction in egg size and increased fecundity, as well as alteration in sex ratios are common (Groves et al., 2022), and have been suggested to be a manifestation of fishing pressure impacts on fish stock (Grabowska and Przybylski, 2015).

Lake Albert, situated within the African Great Lakes network (Salzburger et al., 2014; Thierry et al., 2015; Hamilton et al., 2022), has a rich history of artisanal fisheries dating centuries back

(Worthington, 1929; Holden, 1963), initially targeting large-bodied species like Nile perch and Nile tilapia. However, recent decades have witnessed a significant shift towards small-sized pelagic species, notably *Engraulicypris bredoi* and *Brycinus nurse* (Mbabazi et al., 2012; 2019; Kolding et al., 2019; Nakiyende et al., 2023), driven by factors such as overfishing of large-bodied species and changes in climate and environmental conditions (Wandera, 2000; von Sarnowski, 2004, Nakiyende et al., 2013). Despite the economic importance of these small-sized species, information on their biological and ecological characteristics are lacking (Wandera and Balirwa, 2010; Mbabazi et al., 2012; Nakiyende et al., 2023), posing significant risks like over-exploitation (von Sarnowski, 2004) and stock collapse, as observed in once-dominant large-bodied fish species like *Citharinus citharus* (Worthington, 1929; Holden, 1963; Orach-Meza et al., 1989; Cadwalladr and Stoneman, 1966). These challenges are further compounded by the complexity of the lake's multi-species multi-gear artisanal fishery (Wandera and Balirwa, 2010; Mbabazi et al., 2012), leading to conflicting interests and competing resource demands among fishers (Nakiyende et al., 2013; 2023).

The limited knowledge of the life-history attributes of the diverse exploited species in Lake Albert (Wandera and Balirwa, 2010; Nakiyende et al., 2013; 2023), highlights the critical knowledge gap that needs to be addressed in order to sustainably manage these stocks. Specifically, the available information on biological characteristics of *E. bredoi* and *B. nurse* is inadequate, scanty, and largely based on historical studies in other regions (Ita, 1984; Olopade et al, 2020) and simulated models (Froese et al., 2014; 2017) as summarized in

**Table 6.1-1.** *Engraulicypris bredoi* has a narrow distribution range as it is endemic to Lake Albert (Greenwood, 1966; Wandera and Balirwa, 2010; Riddin et al., 2016). The distribution of *B. nurse* extends to other water bodies including lakes Rudolf (Turkana) and Chad, and Rivers Aswa, Nile, Niger, Gambia, and Senegal (Greenwood, 1966; Bailey, 1994; Getahun, 2007; IUCN, 2022), however, data on its biological characteristics is scarce. Moreover, both species play a critical role as prey for larger-bodied predators such as *Alestes baremose* and *Hydrocynus forskahlii* (Namulemo et al., 2008), indicating their ecological significance within the Lake Albert ecosystem. Therefore, assessing their stocks in relation to their biological characteristics is essential for informed management decisions (Grabowska and Przybylski, 2015).

**Table 6.1-1.** Basic geographical (distribution), biological (life-history traits), and ecological (trophic levels) information available on *Engraulicypris bredoi* and *Brycinus nurse*.

Species	<i>E. bredoi</i>	Reference	<i>B. nurse</i>	Reference
Author	Poll, 1945	( <a href="https://www.fishbase.se/summary/11594">https://www.fishbase.se/summary/11594</a> )	Rüppell, 1832	Olopade et al, 2020
Endemism	Lake Albert	Howes, 1984; Riddin et al., 2016	None	
Environment	Freshwater		Freshwater	
Depth range	Benthopelagic	Riddin, 2016	Pelagic	
Distribution range	Tropical (Africa)	Riddin, 2016	Tropical (Africa)	
IUCN category	Vulnerable (UV)	IUCN, 2022	Least Concern	IUCN, 2022
L_max_historical	45 mm	Lévêque and Daget, 1984	25 mm	Ita, 1984
L50_Unsexed	35 mm (2.6 - 4.7 mm)	( <a href="https://www.fishbase.se/summary/11594">https://www.fishbase.se/summary/11594</a> )	89 mm	Ita, 1984
L50_Males	??		??	
L50_Females	??		??	
Linf	??		??	
K	??		(0.41 - 0.92)	
<b>Model-based data</b>				
Bayesian length-weight: a	0.01000 (0.00244 - 0.04107)	Froese et al., 2014	0.01202 (0.00929 - 0.01556)	Froese et al., 2014
Bayesian length-weight: b	3.04 (2.81 - 3.27)	Froese et al., 2014	2.98 (2.93 - 3.03)	Froese et al., 2014
Phylogenetic diversity index (PD50)	0.5039 (0.5 - 2.0)	Faith, 1992	0.5000 (0.5 - 2.0)	
Trophic level	3.0 ± 0.3 se		2.5 ± 0.2se	
Resilience	High	Froese et al., 2017	High	Froese et al., 2017
Fishing Vulnerability	Low (10 of 100)	Cheung et al., 2007	Low to moderate	Cheung et al., 2007

Given the ecological and socio-economic significance of *B. nurse* and *E. bredoi* in Lake Albert (Wandera and Balirwa, 2010; Mbabazi et al., 2012; Kolding et al., 2019), coupled with the unguided exploitation of these two stocks (Nakiyende et al., 2023), the implementation of sustainable management measures that balance conservation, whilst maximizing economic benefits as enshrined

in FAO (1995) and Uganda's third national development plan (NDP III, 2020) has become crucial. This study aims to bridge the knowledge gaps regarding the life-history attributes of *E. bredoi* and *B. nurse* in Lake Albert, focusing on key parameters outlined above, essential for informed management decisions.

## **6.2. MATERIALS AND METHODS**

### **6.2.1. Study area and sampling procedure**

The primary focus of the study was on the Uganda part of Lake Albert (**Figure 6.2-1**), where fishing using lights is permitted in accordance with the Fish (Fishing) Rules, 2010. Samples of *E. bredoi* and *B. nurse* were collected through a combination of experimental fishing and examination of artisanal catches landed by fishers in this region of Lake Albert.

### **6.2.2. Experimental fishing**

Experimental sampling was conducted from February 2021 to June 2022, encompassing four study sites located within the central region of Uganda's portion of Lake Albert (**Figure 6.2-1**). These sites were further categorized into two broad habitats, with two of the sites situated within the inshore shallow (<20 m) areas, while the other two were positioned within the deep offshore (> 20 m) habitats of Lake Albert. These study sites overlapped with regions commonly frequented by artisanal fishers. Monthly night light fishing experiments were carried out at these locations to collect fish samples, following the standard operating procedures outlined in LVFO (2005) for biological surveys on Lake Victoria. Fishing operations were conducted aboard a motorized flat-transomed fishing vessel, locally known as "ssese flat-at-one-end," utilizing an 8-mm mesh recommended for Lake Albert (Fish (Fishing) Rules, 2010), 8-panel small-seine net. The net was operated through encircling the fish concentrated by light. The experimental surveys replicated the fishing nets employed in artisanal fisheries, with each net panel measuring 2 meters in width (depth) and 100 meters in length.

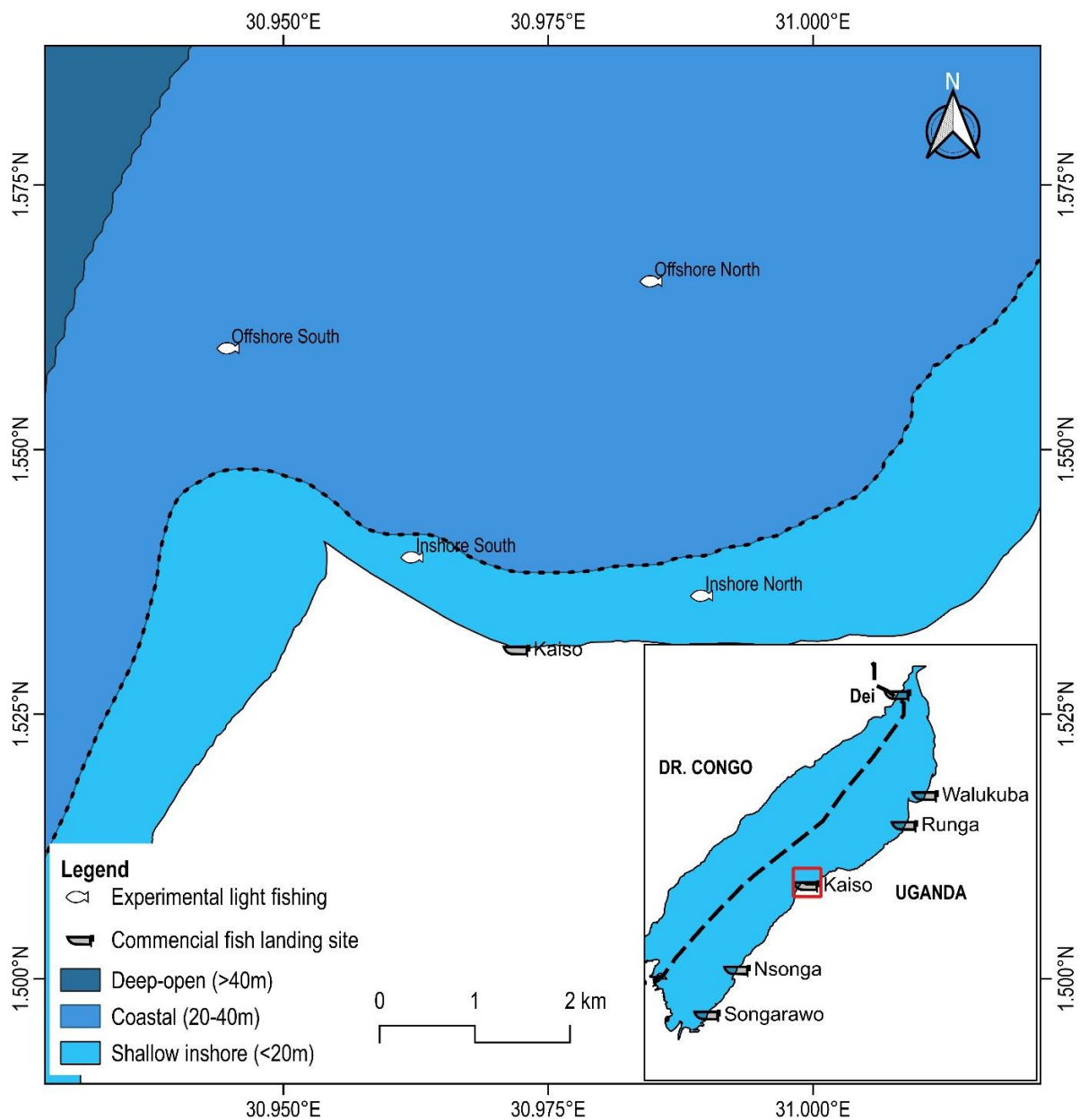
### **6.2.3. Commercial catch evaluation**

The catch data obtained through catch assessment surveys, as detailed in chapter four, were also analyzed and compared with the findings presented in this chapter. It is important to note that artisanal fishers exclusively utilized 5-mm mesh nets of varying panels for fish harvest.

#### 6.2.4. Processing of catch

Both experimental and artisanal catch were processed as follows:

- i. Large individuals (>100 mm, total/Fork length) of the large-bodied species (bycatch) were sorted from each sampled boat/ fish haul and identified to the species level, with the number, weight, and length of each species group recorded.
- ii. The remaining catch, comprising a mixture of the target species (*E. bredoi* and *B. nurse*) and small individuals of the large-bodied bycatch species was weighed after placing in weighing buckets.
- iii. A random sub-sample of 1 kg was taken from the mixed catch and preserved with 5% formalin. Samples were identified by labels containing sampling details including date, station, GPS location, haul number, light type and intensity, as well as species.
- iv. All samples were stored in a large airtight container and transported to the NaFIRRI laboratory for detailed analysis.
- v. Upon arrival at the laboratory, each sample was emptied on to a perforated sieve and rinsed under running tap water to remove excess formalin. The samples were then sorted into species groups. Both individual fish length (mm) and weight (g) of all fish specimens in the sample were recorded.
- vi. For both *E. bredoi* and *B. nurse*, individual lengths were measured and heaped in size groups at 1 mm intervals.
- vii. Ten specimens were randomly selected from each size class. Their individual standard length (mm) and weight (g) was measured, and they were dissected to determine sex and gonad maturity. If specimens in a given size group were fewer than 10, all the fish were dissected for examination.



**Figure 6.2-1.** Sites sampled for experimental fishing and artisanal catch evaluation on Lake Albert, Uganda between February 2021 and June 2022.

### 6.2.5. Measurement of length, weight, sex, and gonad maturity status.

Fish weight (in grams) and standard length (SL, in millimeters) were measured using a precise digital weighing scale with an accuracy of 0.01 g and a measuring board with 10 mm gradations, respectively. To ensure accuracy, fish of similar lengths were grouped, with 10 individuals selected

randomly from each length category for further examination. These fish were individually re-measured, dissected, and their internal anatomy examined to determine sex and gonad maturity under a binocular scope (x45 magnification). Sex was categorized as immature (IMM), Male (M), and Female (F). Gonadal maturity was assessed using Kesteven's gonad maturity index, employing a seven-point scale (I–VII) (Ricker, 1974 cited in LVFO, 2005; West, 1990; Núñez and Duponchelle, 2009; Brown-Peterson et al., 2011). Fish gonads classified as stage I-III were considered immature, while stages IV-VI indicated maturity for both male and female specimens.

**6.2.6. Data analysis.**

The Fish Stock Analysis (FSA), specifically the second version of Fish Stock Assessment Tool (FISAT II) (Gayanaló and Pauly, 1997; King, 2013) and TropFishR packages (Mildenberger et al., 2017; Taylor and Mildenberger, 2017; Ogle et al., 2023) were utilized. The FSA package offers functions for fitting various models to data, encompassing length-based, age-based, and surplus production models. The TropFishR package extends the analysis capabilities to tropical fish stocks, enabling estimation of key fishery parameters like population size structure and size at sexual maturity.

**6.2.7. Sex ratio.**

The sex ratio indicating the proportion of male and female individuals in a population was computed (Wilson and Hardy, 2002; Ogburn, 2019). A Chi-square test of independence (McHugh, 2013; Turhan, 2020) was performed to test for independence of these proportions across habitat.

**6.2.8. Estimation of size at 50% maturity (Lm50).**

Size at 50% maturity ( $L_{m50}$ ), the length at which 50% of the fish attain sexual maturity, was determined for each sex by assessing the proportion of mature fish in various length classes (Chen and Paloheimo, 1994) using a Generalized Linear Model (GLM) with binomial distribution. This analysis was conducted using the TropFishR packages (Mildenberger et al., 2017), using equation 1. A binomial distribution (0 = immature, 1 = mature) with a log odds (logit) link was utilized for the GLM.

$$P_L = \frac{1}{1 + e^{-K(L-L_{50})}} \dots\dots\dots \text{Equation 1}$$





**Maximum life span ( $t_{max}$ )**, the maximum age a fish can attain was calculated as the age at 95% of  $L_{\infty}$  (length at infinity) using parameters of von Bertalanffy growth function estimated above as:

$$t_{max} = t_0 + \frac{3}{K} \dots \dots \dots \text{Equation 6}$$

**Growth performance ( $\phi'$ )**, used to compare different populations of the same species between different habitats of the lake to get an indication of habitat conditions and differences in stocks was calculated using the formula in equation 4 (Pauly, 1980):

$$\phi' = \text{Log}_{10}K + 2 \text{Log}_{10}L_{\infty} \dots \dots \dots \text{Equation 7}$$

Where  $K$  is expressed on an annual basis and  $L_{\infty}$  is in cm

**Estimation of mortality rates: total mortality (Z), natural mortality (M), and fishing mortality (F)**

Mortality rate was estimated based on the lake surface temperature of (RST) 27.8°C (Beverton and Holt, 1956).

$$Z = F + M \dots \dots \dots \text{Equation 8}$$

Where:  $Z$  is the total mortality,  $F$  is the fishing mortality,  $M$  is the natural mortality. The VPA model iteratively adjusted the  $F$  parameter to minimize the difference between observed and predicted length-frequency distributions, thus yielding accurate estimates of fishing mortality rates.

**Estimation of exploitation rate (E)**

Exploitation rate was calculated as:

$$E = \frac{F}{Z} \dots \dots \dots \text{Equation 9}$$

**Biomass-Based Reference Points**

**Biomass at maximum sustainable yield**

The biomass limit reference points, Biomass at Maximum Sustainable Yield ( $B_{MSY}$ ), was determined using the following equation (Schaefer, 1954):

$$BMSY = \max \left( \frac{dB}{dF} \right) \dots \dots \dots \text{Equation 10}$$

Here,  $B$  signifies biomass. The model projected the population's biomass trajectory for varying levels of fishing mortality rates to determine these reference points.

### **Yield-per-Recruit (YPR)**

The Yield-per-Recruit (YPR) model, a standard approach for assessing population productivity, was used to estimate the yield generated by harvesting a single recruit at different ages and sizes (Sparre and Venema, 1998). YPR analysis accounts for species-specific growth, mortality, and age-at-recruitment parameters to provide insights into optimal harvesting strategies and potential yields. YPR focuses on the contribution of individual cohorts to overall yield under varying fishing pressures.

$$YPR = \frac{Y}{R} \dots\dots\dots \text{Equation 11}$$

Where  $R$  represents recruitment. For this analysis, input data included length-frequency distributions, growth parameters ( $L_{\infty}$ ,  $K$ ,  $t_0$ ), natural mortality rates ( $M$ ), fishing mortality rates ( $F$ ), and size at first capture ( $L_c$ ) for *E. bredoi* and *B. nurse*.

### **Biomass per Recruit (BPR)**

The biomass per recruit (BPR), a metric to used evaluate the biomass available for each recruit was estimated as follows:

$$BPR = \frac{B}{R} \dots\dots\dots \text{Equation 12}$$

BPR used the same life-history inputs as YPR (length-frequency data, growth parameters,  $M$ ,  $F$ , and  $L_c$ ) to assess biomass accumulation per recruit under varying fishing scenarios.

### **Estimation of size and age at first capture**

Understanding size at first capture (the average size at which fish become vulnerable fishing gear) and age at first capture (the average age when they are first captured) is crucial for assessing a stock's vulnerability to fishing mortality (Maunder and Punt, 2013; Froese et al., 2016). These metrics inform sustainable fisheries management by identifying the minimum size and age at which fish should be harvested to ensure their reproductive success and long-term population viability. Size and age at first capture were estimated using a logistic regression function within the TropFishR package (Mildenberger et al., 2017; Taylor and Mildenberger, 2017).

## 6.3. RESULTS

### 6.3.1. Sex ratio.

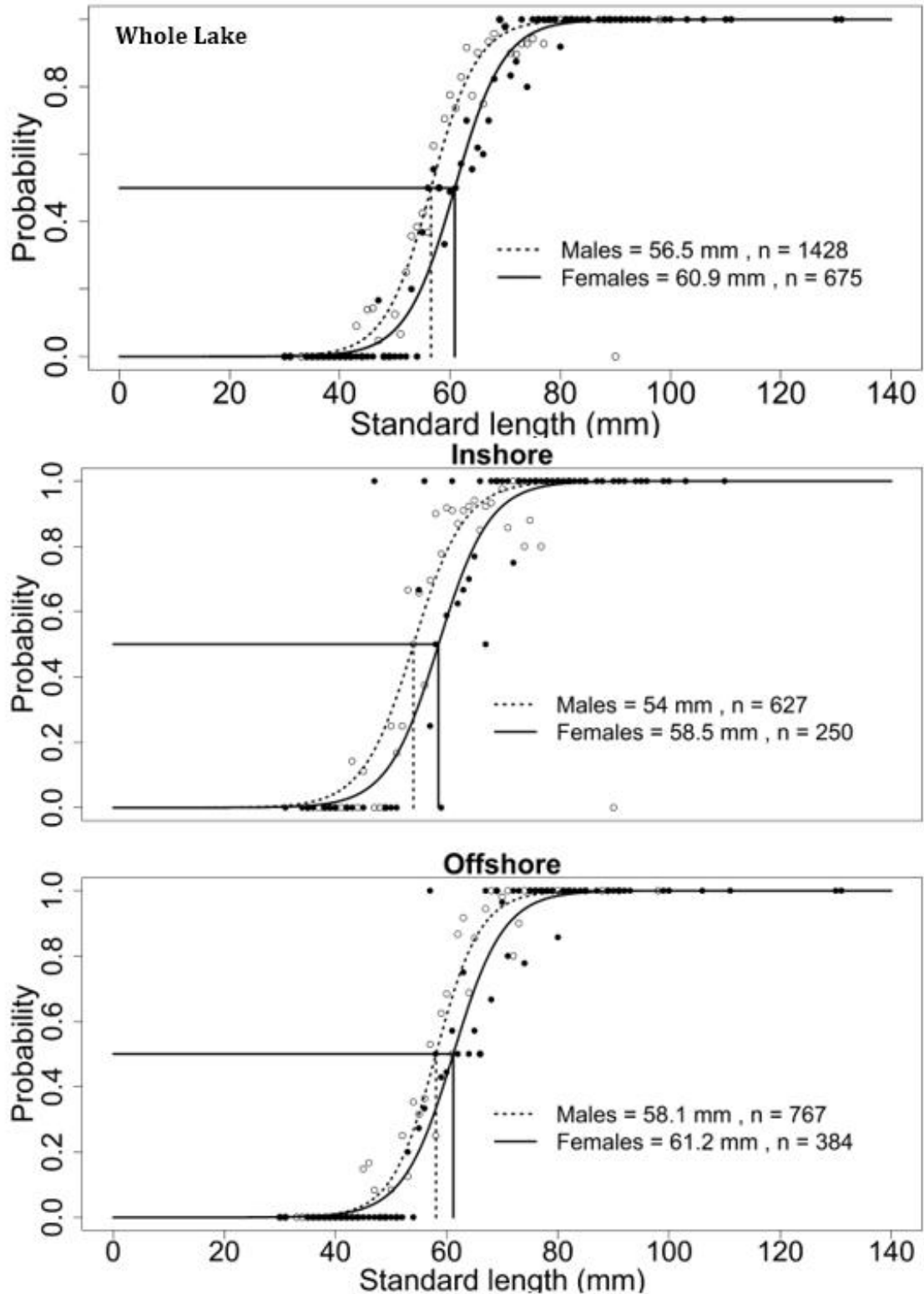
An analysis of 2103 samples of *B. nurse* (comprising 675 females and 1428 males) and 2593 samples of *E. bredoi* (consisting of 1404 females and 1189 males) from experimental catch revealed a male-biased sex ratio for *B. nurse* (1 male for every 2.11 females), while *E. bredoi* exhibited a sex ratio of 1.18 females for every 1 male. Statistically significant differences between the observed and expected values were recorded for *E. bredoi* ( $\chi^2 = 17.864$ , DF=1,  $p < 0.05$ ) but not *B. nurse* ( $\chi^2 = 269.6$ , DF=1,  $p > 0.05$ ).

### 6.3.2. Size (Length) at 50% (L<sub>m50</sub>) maturity.

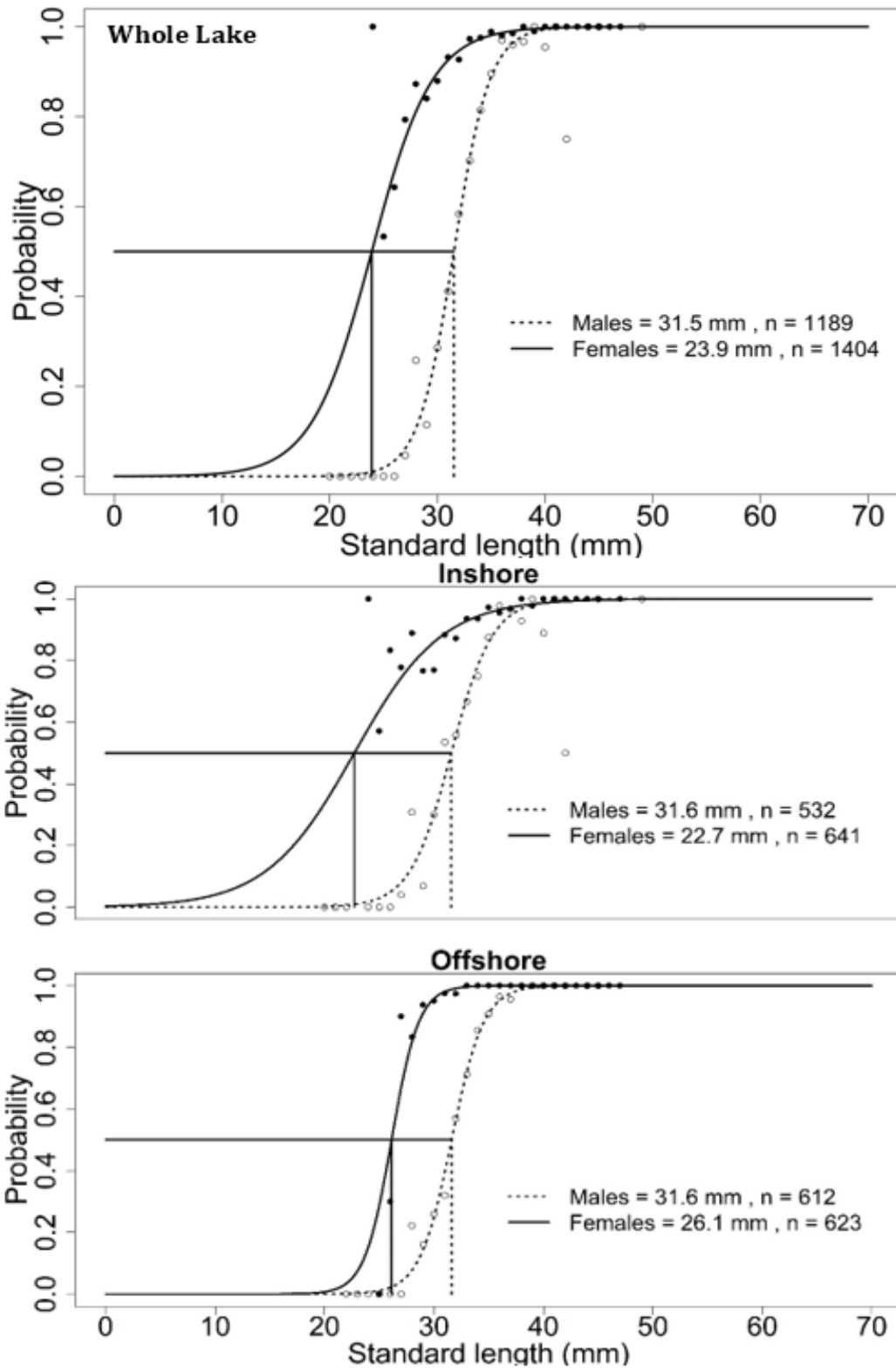
Size at maturity estimated for fish captured in experimental sampling revealed that females of *B. nurse* matured at a larger size (60.9 mm SL) than the males (56.5 mm, SL) across habitats (**Figure 6.3-1**). In contrast, *E. bredoi* males matured at a larger size (31.5 mm, SL) than the females (23.9 mm, SL) (**Figure 6.3-2**). However, both species exhibited habitat-related variations in L<sub>m50</sub>, with offshore populations maturing at larger sizes compared to the inshore populations (**Figure 6.3-1 & Figure 6.3-2**).

### 6.3.3. Proportion of mature and immature populations of *E. bredoi* and *B. nurse* across months.

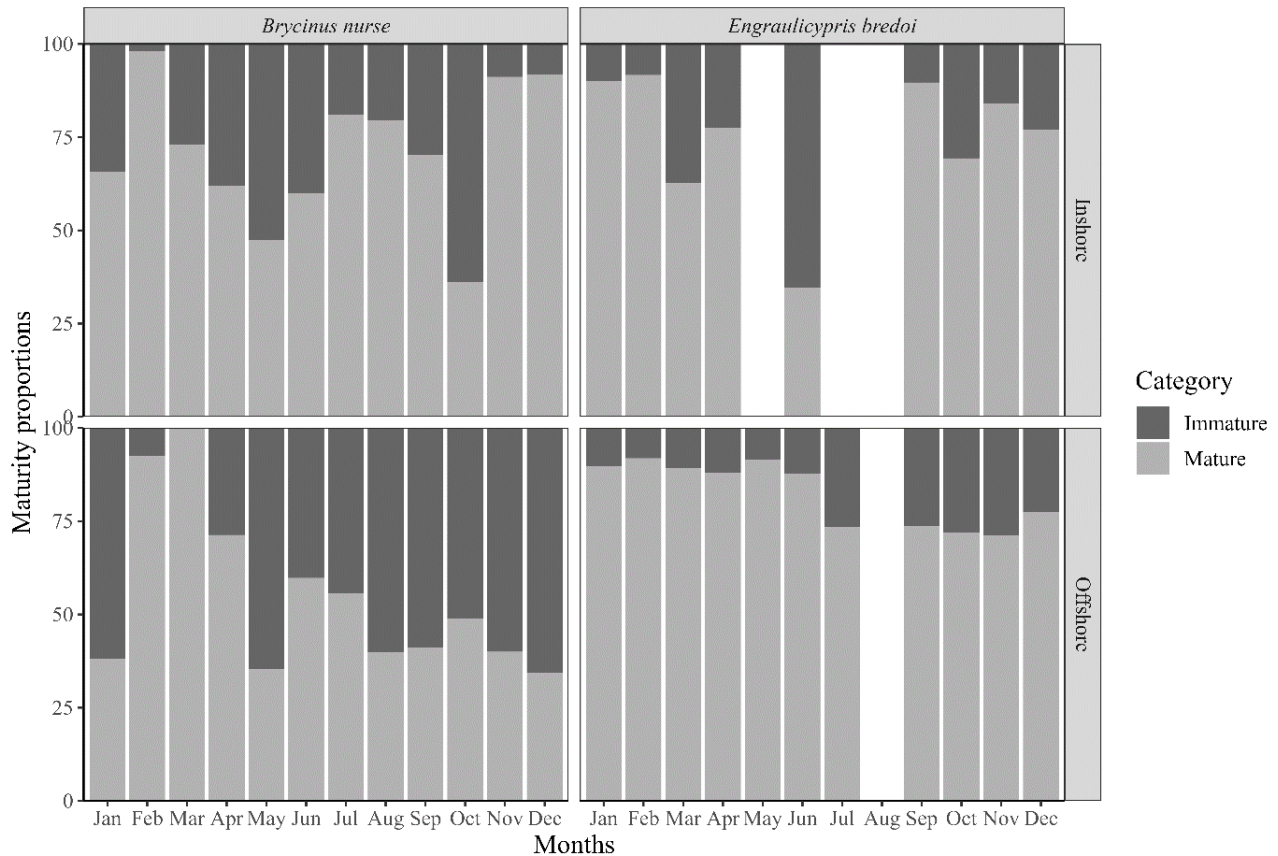
A comparison of mature and immature proportions of *E. bredoi* and *B. nurse* captured in experimental sampling across habitats and months in Lake Albert revealed distinct patterns for each species (**Figure 6.3-3**). The proportion of mature *E. bredoi* individuals was consistently high in both offshore and inshore habitats across months (**Figure 6.3-3**). The mature fish constituted 60% to 90% of the total population size, except for June, which recorded a higher proportion (63.7%) of immature individuals within the inshore habitat, suggesting a potential breeding peak. *Brycinus nurse* exhibited a contrasting pattern, with the offshore habitat registering a higher proportion of immature fish for most months, while the inshore tended to harbor more mature individuals during the majority months (**Figure 6.3-3**). Exceptions were observed in the months of February (immature = 7.8%), March (immature = 0.0%), and April (immature = 47.6%) for the offshore habitat, and in April-June and October for the inshore habitat (**Figure 6.3-3**).



**Figure 6.3-1.** Estimated length at 50% maturity of female and male *Brycinus nurse* in Lake Albert, Uganda based on experimental catch data.



**Figure 6.3-2.** Estimated length at 50% maturity of female and male *Engraulicypris bredoi* in Lake Albert, Uganda, based on experimental catch data.

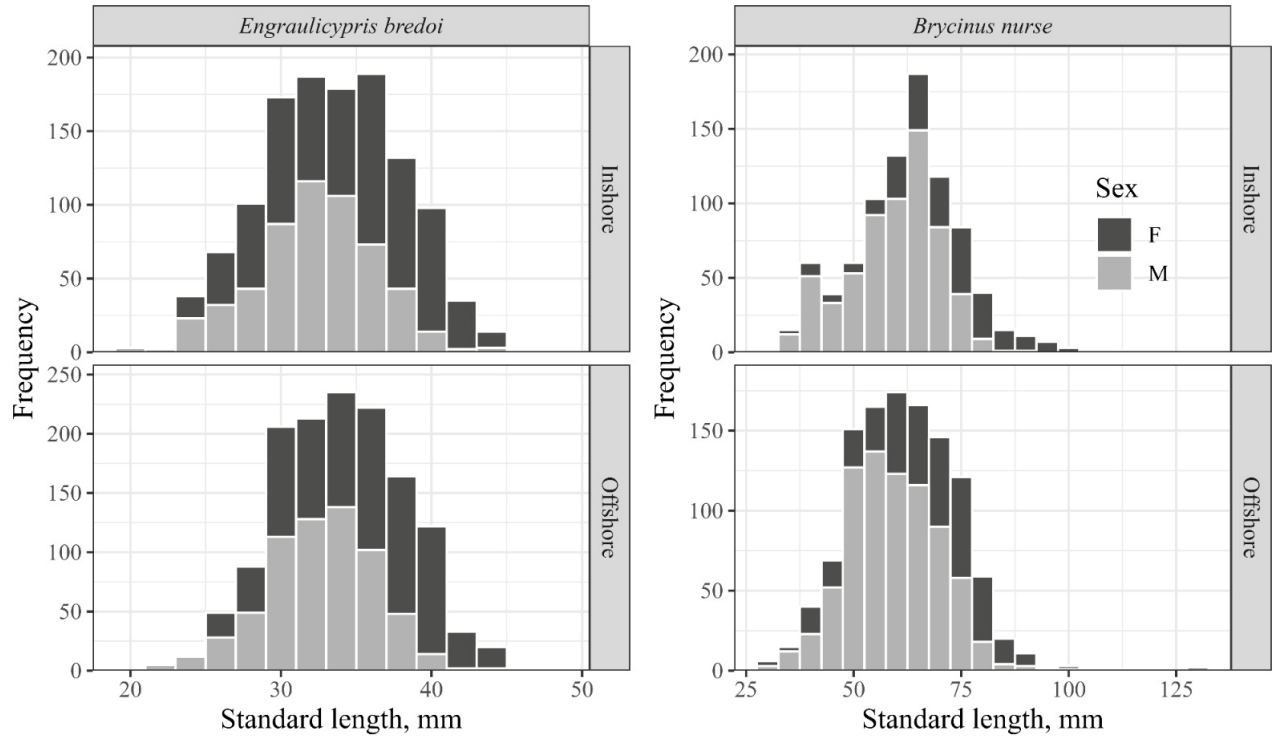


**Figure 6.3-3.** Proportion of mature and immature *Brycinus nurse* and *Engraulicypris bredoi* in the inshore and offshore habitats of Lake Albert, Uganda, based on experimental catch data.

### 6.3.4. Population Size Structure.

#### 6.3.4.1. Population size structure between habitats using experimental nets.

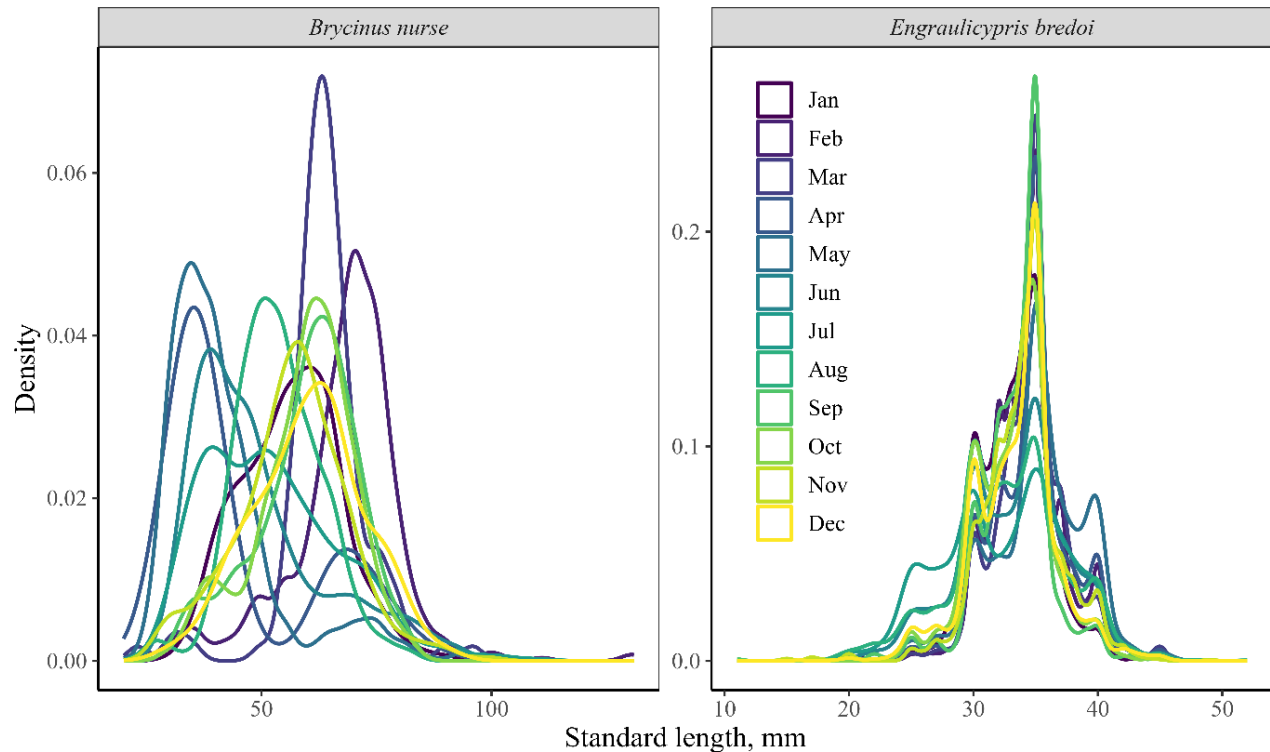
Both *B. nurse* and *E. bredoi* displayed a unimodal normal distribution pattern of length-frequency (standard length) across habitats and sex (**Figure 6.3-4**), with a mean length of 34.1 mm for *E. bredoi* and 52.7 mm for *B. nurse*. The offshore habitat revealed larger fish of *E. bredoi* (mean length of 35.7 mm for females and 33.1 mm for males) in contrast to the inshore habitat (mean length of 34.7 mm for females and 32.8 mm for males). Conversely, the inshore habitat depicted larger fish of *B. nurse* (mean length of 69.8 mm for females and 59.5 mm for males) compared to the offshore habitat (mean length of 66.3 mm for females and 59.2 mm for males) (**Figure 6.3-4**).



**Figure 6.3-4.** Size (length) distribution of *Engraulicypris bredoi* and *Brycinus nurse* in Lake Albert, Uganda presented by habitat among sexes, based on experimental catch data.

#### 6.3.4.2. Population size structure between months.

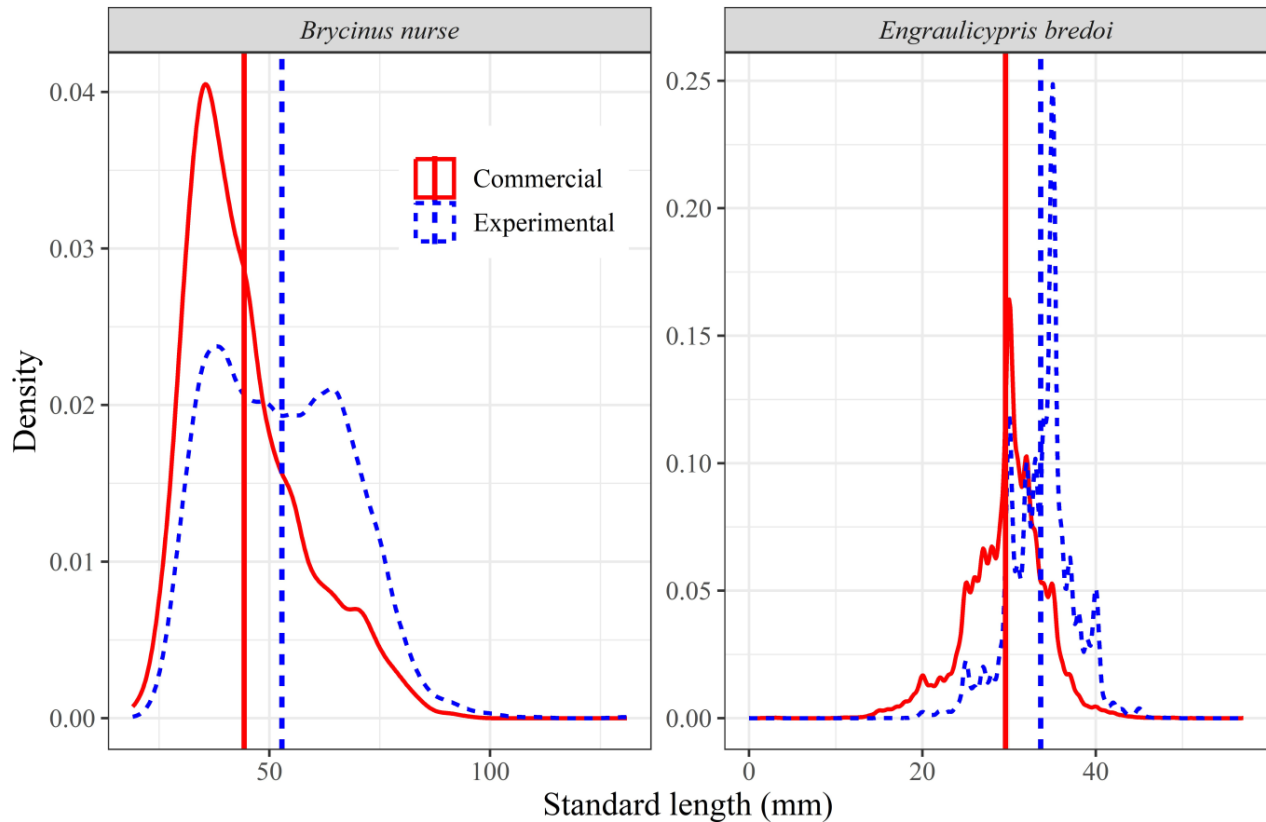
*Engraulicypris bredoi* exhibited a relatively normal length-frequency distribution across months, with a mean length of 34.2 mm (**Figure 6.3-5**). In contrast, *Brycinus nurse* displayed a trimodal distribution, indicating three discernible peaks in its length frequency distribution. The first peak occurred between April and June (34 to 39 mm, SL), followed by an intermediate peak in August (51 mm, SL), and the third peak manifested between September and March (62 to 70 mm, SL) (**Figure 6.3-5**).



**Figure 6.3-5.** Variation in length (mm) sizes of *Brycinus nurse* and *Engraulicypris bredoi* in Lake Albert, Uganda, based on experimental catch data.

**6.3.4.3. Population size structure between experimental and artisanal (commercial) catch.**

A comparison of the length-frequency distribution of *E. bredoi* and *B. nurse* populations in the artisanal and experimental catches on Lake Albert, reveal a consistent pattern of smaller-sized population in the artisanal catches (**Figure 6.3-6**). The mean length of *B. nurse* in the artisanal and experimental catches were 43.5 mm and 53 mm, respectively. Similarly, the mean length of *E. bredoi* was 29.8 mm and 34.3 mm in the artisanal catch and experimental catch, respectively (**Figure 6.3-6**).



**Figure 6.3-6.** Size structure of *Brycinus nurse* and *Engraulicypris bredoi* landed in artisanal (red) and experimental (blue) catches on Lake Albert, Uganda, based on experimental and artisanal catch data. The vertical lines denote mean lengths.

### 6.3.5. Length-weight relationship.

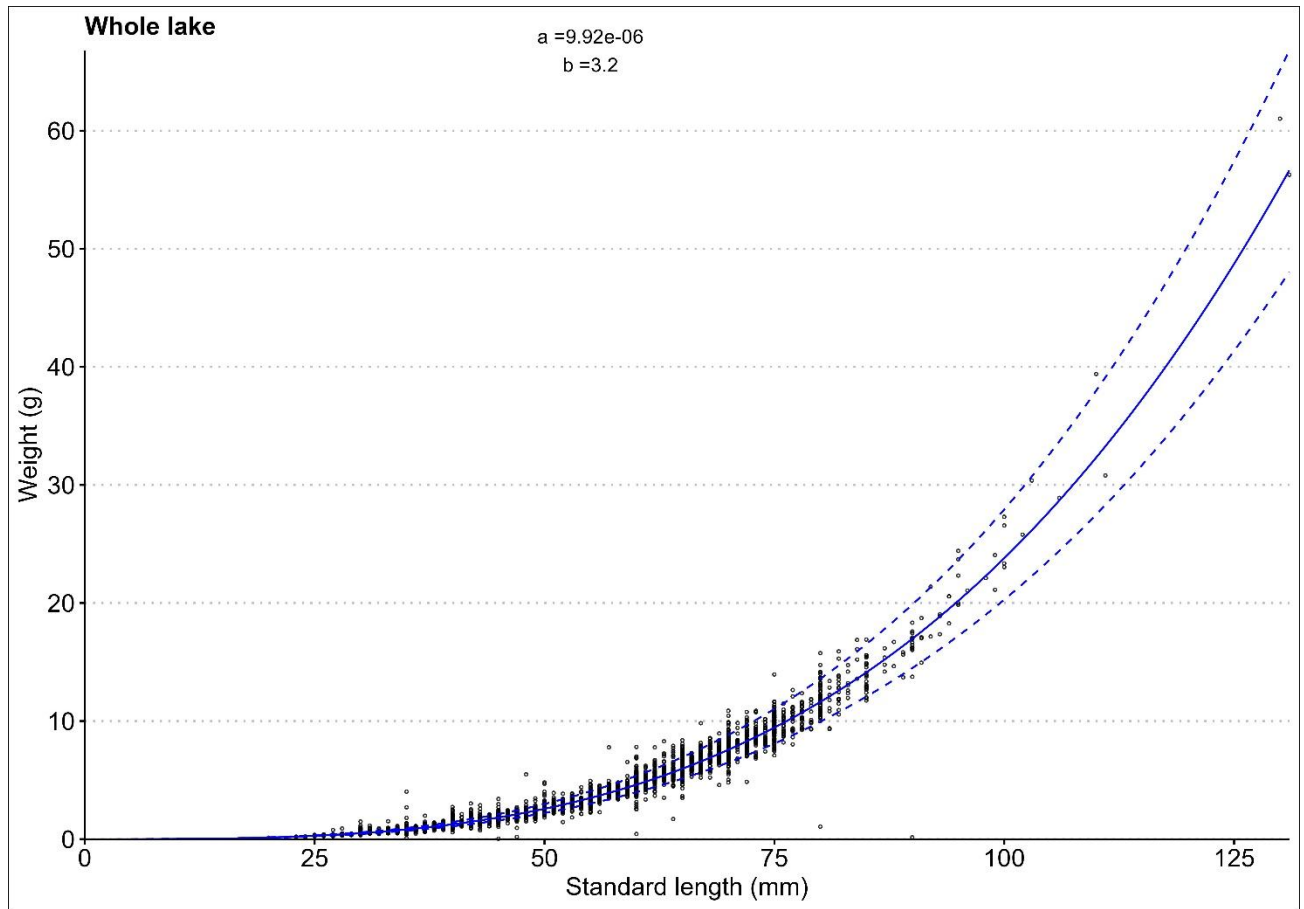
Length-weight relationships analyzed based on 4662 samples of *B. nurse* and 2784 samples of *E. bredoi*, obtained from the experimental catch revealed positive allometric growth in both species (Figure 6.3-7; Figure 6.3-8).

The length-weight relationship equations were derived as follows:

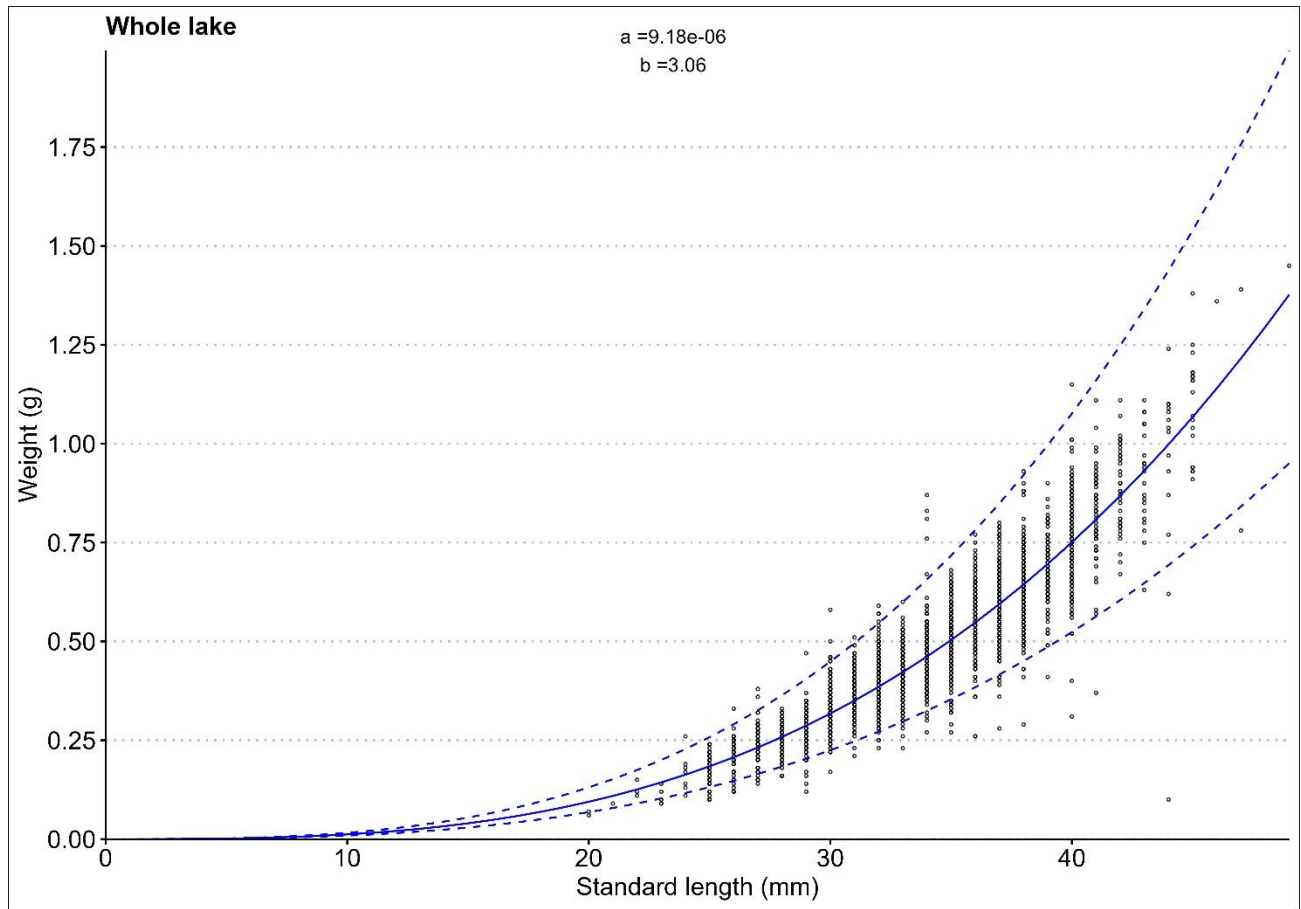
For *B. nurse*: Weight (W) = 0.00000992 \* Length (L)<sup>3.21</sup> ..... Equation 4.

For *E. bredoi*: Weight (W) = 0.00000918 \* Length (L)<sup>3.06</sup> .....Equation 5.

The overall coefficient 'b' for both *B. nurse* and *E. bredoi* in the whole lake was estimated at 3.21 ± 0.02 (95% CI) and 3.06 ± 0.07 (95% CI), respectively, indicating that these fish become slightly fatter as they grow longer. However, variation in 'b' values was observed between inshore and offshore habitats among sexes of both species (**Table 6.3-1**).



**Figure 6.3-7.** Length-weight relationship for *Brycinus nurse* in Lake Albert, Uganda, based on experimental data.



**Figure 6.3-8.** Length-weight relationship for *Engraulicypris bredoi* in Lake Albert, Uganda, based on experimental data.

**Table 6.3-1.** The weight-length relationship parameters 'a' and 'b' for *Engraulicypris bredoi* and *Brycinus nurse* in Lake Albert, Uganda, based on experimental catch data.

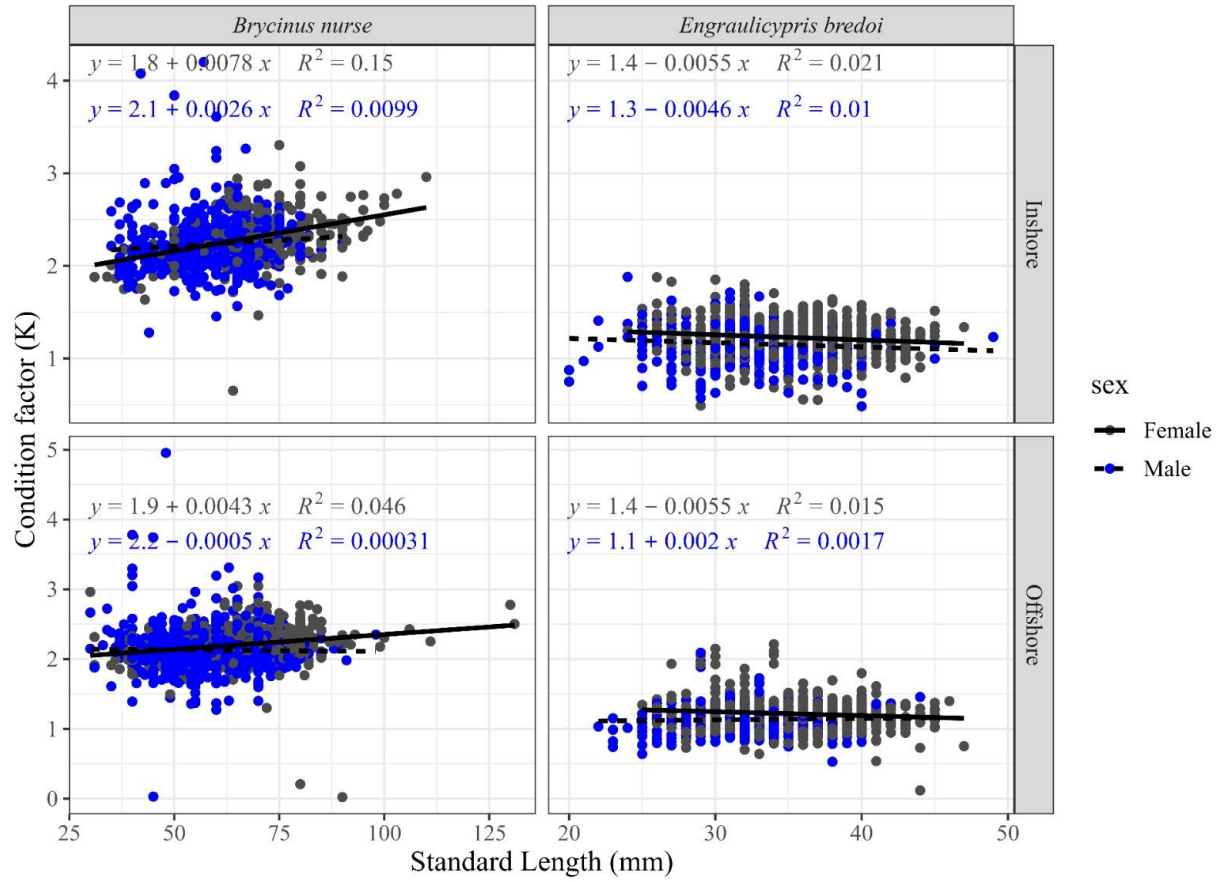
Species	Habitat	Parameter	Estimate	std.error	Statistic	p.value	conf.low	conf.high
<i>B. nurse</i>	Combined	a	9E-06	0.0375	-310	0	8.3E-06	9.65E-06
<i>B. nurse</i>	Combined	b	3.21	0.00955	336	0	3.19	3.23
<i>B. nurse</i>	Inshore	a	9.9E-06	0.0488	-263	0	9.0E-06	1.1E-05
<i>B. nurse</i>	Inshore	b	3.20	0.0122	263	0	3.17	3.22
<i>B. nurse</i>	Offshore	a	9.5E-06	0.0517	-224	0	8.6E-06	1.10E-05
<i>B. nurse</i>	Offshore	b	3.19	0.0133	240	0	3.16	3.22
<i>B. nurse</i>	Female	a	1.3E-05	0.18	-62.6	3.28E-273	9.1E-06	1.84E-05
<i>B. nurse</i>	Female	b	3.13	0.0428	73.1	2.19e-310	3.05	3.21
<i>B. nurse</i>	Male	a	1.7E-05	0.0998	-110	0	1.4E-05	0.000021
<i>B. nurse</i>	Male	b	3.05	0.0245	125	0	3.01	3.1
<i>E. bredoi</i>	Combined	a	9.2E-06	0.132	-87.9	0	7.1E-06	1.19E-05
<i>E. bredoi</i>	Combined	b	3.06	0.0374	82	0	2.99	3.14
<i>E. bredoi</i>	Inshore	a	1.4E-05	0.121	-92.2	0	1.1E-05	1.8E-05
<i>E. bredoi</i>	Inshore	b	2.95	0.0345	85.6	0	2.89	3.02
<i>E. bredoi</i>	Offshore	a	9.2E-06	0.132	-87.9	0	7.1E-06	1.2E-05

<i>E. bredoi</i>	Offshore	b	3.06	0.0374	82.0	0	2.99	3.14
<i>E. bredoi</i>	Female	a	2.1E-05	0.126	-85.9	0	1.6E-05	2.62E-05
<i>E. bredoi</i>	Female	b	2.85	0.0353	80.6	0	2.78	2.92
<i>E. bredoi</i>	Male	a	1.1E-05	0.136	-84.1	0	8.5E-06	1.45E-05
<i>E. bredoi</i>	Male	b	3.00	0.0388	77.3	0	2.93	3.08

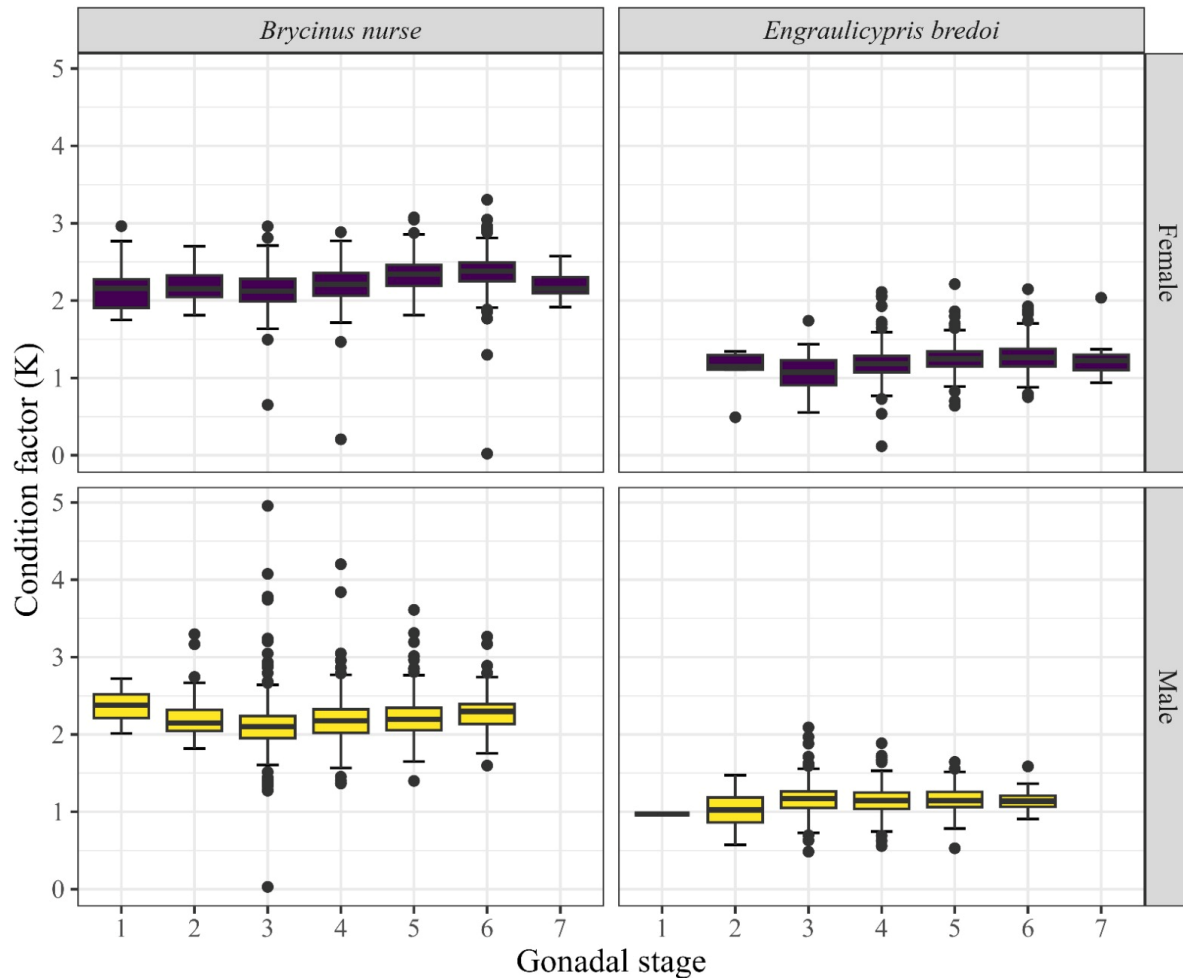
### 6.3.6. Condition factor.

The mean Fulton's condition factor (K) was 2.08 for *Brycinus nurse* and 1.27 for *Engraulicypris bredoi* (**Figure 6.3-9**). To substantiate observed patterns, statistical tests were conducted to examine differences in condition factor between habitats and among gonad development stages. A two-way Analysis of Variance (ANOVA), with habitat (inshore vs offshore) and sex as fixed factors, indicated no statistically significant difference in condition factor between habitats for either *B. nurse* or *E. bredoi* ( $p > 0.05$ ). Similarly, no significant differences in condition factor were detected among gonad development stages ( $p > 0.05$ ), confirming that habitat type did not systematically influence fish condition (**Figure 6.3-9**) or gonadal development (**Figure 6.3-10**).

Despite the absence of significant habitat-related effects, sex-based patterns were evident. Females of *E. bredoi* exhibited marginally higher condition factors than males across both habitats, although these differences were weak and not statistically significant ( $p > 0.05$ ). For *B. nurse*, linear regression analysis revealed a significant positive relationship between condition factor and standard length ( $p < 0.05$ ), indicating improved somatic condition with increasing size. In contrast, *E. bredoi* showed relatively stable condition factors across size classes, with very weak and non-significant length-condition relationships ( $R^2 < 0.02$ ), suggesting size-independent condition within the sampled range (Figure 39)..



**Figure 6.3-9.** Condition factor (K) of *Brycinus nurse* and *Engraulicypris bredoi* in Lake Albert, Uganda between habitats and sex, based on experimental catch data.



**Figure 6.3-10.** Condition factor (K) of *Engraulicypris bredoi* and *Brycinus nurse* in Lake Albert, Uganda by gonadal maturity stage, based on experimental catch data.

### 6.3.7. Estimated growth parameters for *Engraulicypris bredoi* and *Brycinus nurse*

#### von Bertalanffy Growth Parameters $L_{\infty}$ , $K$ , $t_{max}$ , $\emptyset$ , and $t_0$

The population dynamics and exploitation parameters of *Brycinus nurse* and *Engraulicypris bredoi* in Lake Albert reveal notable interspecific differences in growth characteristics, mortality, and fishery reference points (**Table 6.3-2**). *Brycinus nurse* attained a higher asymptotic length ( $L_{\infty} = 147.61$  mm) compared to *E. bredoi* ( $L_{\infty} = 54.20$  mm), indicating its larger maximum body size potential under optimal conditions. However, *E. bredoi* exhibited a higher growth coefficient ( $K = 0.23$  year<sup>-1</sup>) than *B. nurse* ( $K = 0.12$  year<sup>-1</sup>), suggesting faster attainment of its maximum size.

The theoretical age at zero length ( $t_0$ ) was estimated at 0.63 years for *B. nurse* and 0.35 years for *E. bredoi*, with corresponding maximum lifespans ( $t_{max}$ ) of 3.1 and 0.8 years respectively. The growth performance index ( $\phi'$ ) was slightly higher in *E. bredoi* (3.24) than *B. nurse* (2.98), consistent with its faster growth (**Table 6.3-2**).

### Mortality and exploitation rates

Mortality estimates indicated that *E. bredoi* experienced higher natural ( $M = 0.27 \text{ year}^{-1}$ ) and total mortality ( $Z = 0.66 \text{ year}^{-1}$ ) compared to *B. nurse* ( $M = 0.16 \text{ year}^{-1}$ ;  $Z = 0.45 \text{ year}^{-1}$ ). Consequently, fishing mortality was also higher in *E. bredoi* ( $F = 0.39 \text{ year}^{-1}$ ) than in *B. nurse* ( $F = 0.29 \text{ year}^{-1}$ ), with corresponding exploitation rates (E) of 0.59 and 0.64, respectively (**Table 6.3-2**).

### Yield-Per-Recruit (YPR) and Biomass-Per-Recruit (BPR)

Yield-per-recruit (YPR) analyses showed higher predicted yields at  $F_{0.1}$  and  $F_{max}$  for *B. nurse* (48.79 g and 50.86 g) than for *E. bredoi* (58.47 g and 88.63 g). Biomass per recruit (BPR) estimates followed a similar trend, being highest at  $F_{0.5}$ : 781.44 g (*B. nurse*) and 357.09 g (*E. bredoi*), indicating greater biomass retention under conservative fishing levels (**Table 6.3-2**).

The current catches were estimated at 0.19 tonnes for *B. nurse* and 0.09 tonnes for *E. bredoi*, with corresponding current yields of 3233.02 tonnes and 35.62 tonnes, and biomasses of 97209.29 tonnes and 516.61 tonnes. Length at first capture ( $L_c$ ) was lower for *B. nurse* (27.5 mm) than for *E. bredoi* (31 mm), indicating earlier recruitment to fishing gear (**Table 6.3-2**).

**Table 6.3-2.** Growth parameters of *B. nurse* and *E. bredoi* in Lake Albert based on length frequency data collected between February 2021 and June 2022.

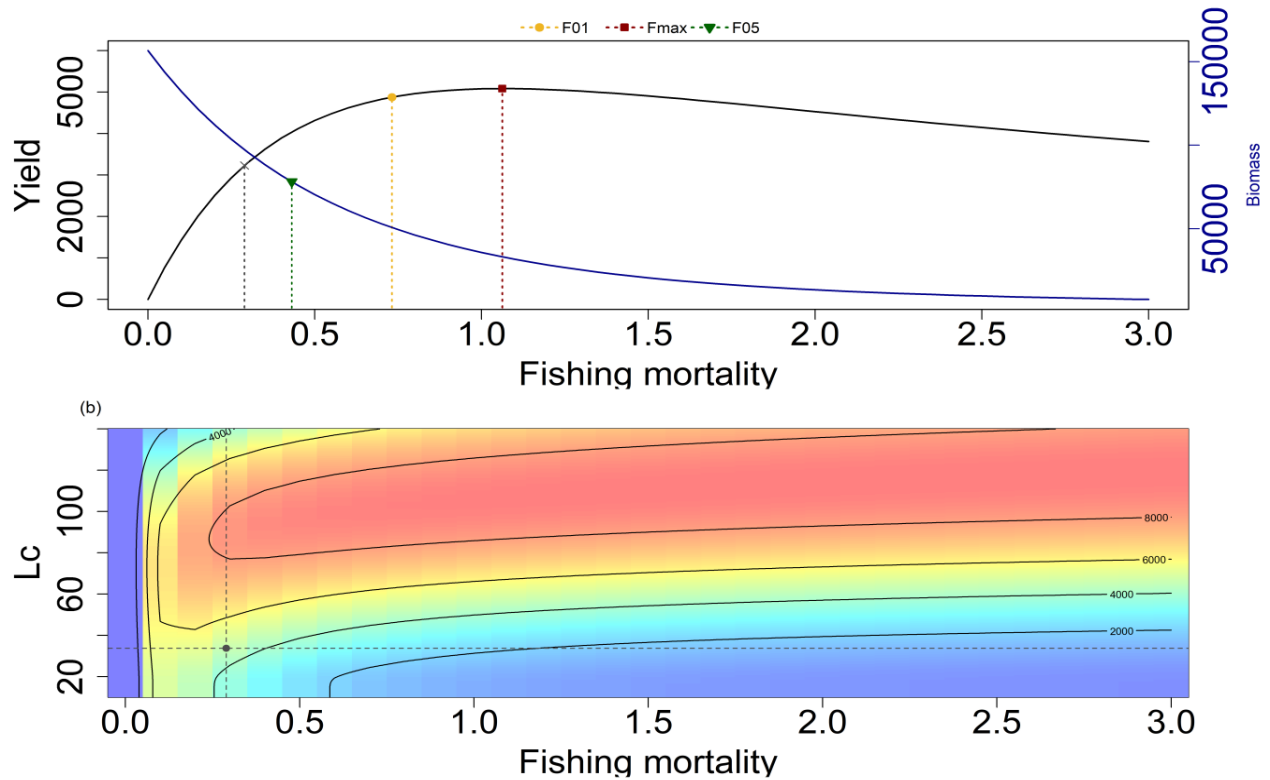
Parameter	Description	<i>B. nurse</i>	<i>E. bredoi</i>
$L_{\infty}$ (mm)	Asymptotic length, representing the theoretical maximum average size a fish can attain under optimal conditions.	147.61	54.20
K ( $\text{year}^{-1}$ )	Growth coefficient (von Bertalanffy growth rate), indicating how quickly a fish approaches its asymptotic length ( $L_{\infty}$ ) per year.	0.12	0.23
$t_0$ (years)	Theoretical age at zero length, indicating age at which a fish would have zero length if it were present in the population from the beginning according to the growth curve.	0.63 yrs	0.35 yrs

$t_{\max}$ (years)	Maximum observed or estimated age of the fish species in the population.	3.1	0.8
$\emptyset$	Growth performance indicator, a composite index that integrates growth rate (K) and asymptotic length ( $L_{\infty}$ ), used for comparing growth performance across populations or species.	2.98	3.24
M (year <sup>-1</sup> )	Natural mortality rate, representing the annual rate of death from natural causes (including disease, predation, pollution) other than fishing.	0.16	0.27
Z (year <sup>-1</sup> )	Total mortality rate, representing combined annual rate of death due to all causes (fishing and natural mortality).	0.45	0.66
F (year <sup>-1</sup> )	Fishing mortality rate, representing the annual rate of death due to fishing.	0.29	0.39
$F_{0.1}$ (year <sup>-1</sup> )	Fishing mortality rate that produces a marginal increase in YPR, often used as precautionary target reference point to support sustainable exploitation.	0.73	1.18
$F_{\max}$ (year <sup>-1</sup> )	Fishing mortality rate that provides maximum yield-per-recruit.	1.06	5.00
$F_{0.5}$ (year <sup>-1</sup> )	Fishing mortality rate that maintains 50% of the spawning biomass relative to its unfished state.	0.43	1.31
$E_{0.1}$	Fishing mortality effort corresponding to $F_{0.1}$ .	1.63	1.78
$E_{\max}$	Fishing mortality effort corresponding to $F_{\max}$ .	2.37	7.54
$E_{0.5}$	Fishing mortality effort corresponding to $F_{0.5}$ .	0.96	1.98
YPR_ $F_{0.1}$ (g recruit <sup>-1</sup> )	Yield per recruit at $F_{0.1}$ , the predicted catch weight from one recruit fished at the $F_{0.1}$ level.	48.79	58.47
YPR_ $F_{\max}$ (g recruit <sup>-1</sup> )	Yield per recruit at $F_{\max}$ , the predicted catch weight from one recruit fished at the $F_{\max}$ level.	50.86	88.63
YPR_ $F_{0.5}$ (g recruit <sup>-1</sup> )	Yield per recruit at $F_{0.5}$ , the predicted catch weight from one recruit fished at the $F_{0.5}$ level.	40.40	59.91
BPR_ $F_{\max}$ (grams)	Biomass per recruit at $F_{\max}$ , expected remaining biomass per recruit after fishing at $F_{\max}$ level.	331.63	103.11
BPR_ $F_{0.5}$ (grams)	Biomass per recruit at $F_{0.5}$ , the expected remaining biomass per recruit after fishing at $F_{0.5}$ level.	781.43	357.09
curr.E	Current exploitation rate (current fishing effort relative to total mortality).	0.64	0.59
curr.C (tonnes)	Current catch, the total weight of fish landed from the stock over a given period.	0.19	0.09
curr.Y (tonnes)	Current yield, sustainable portion of the catch contributing to long-term benefits.	3233.02	35.62

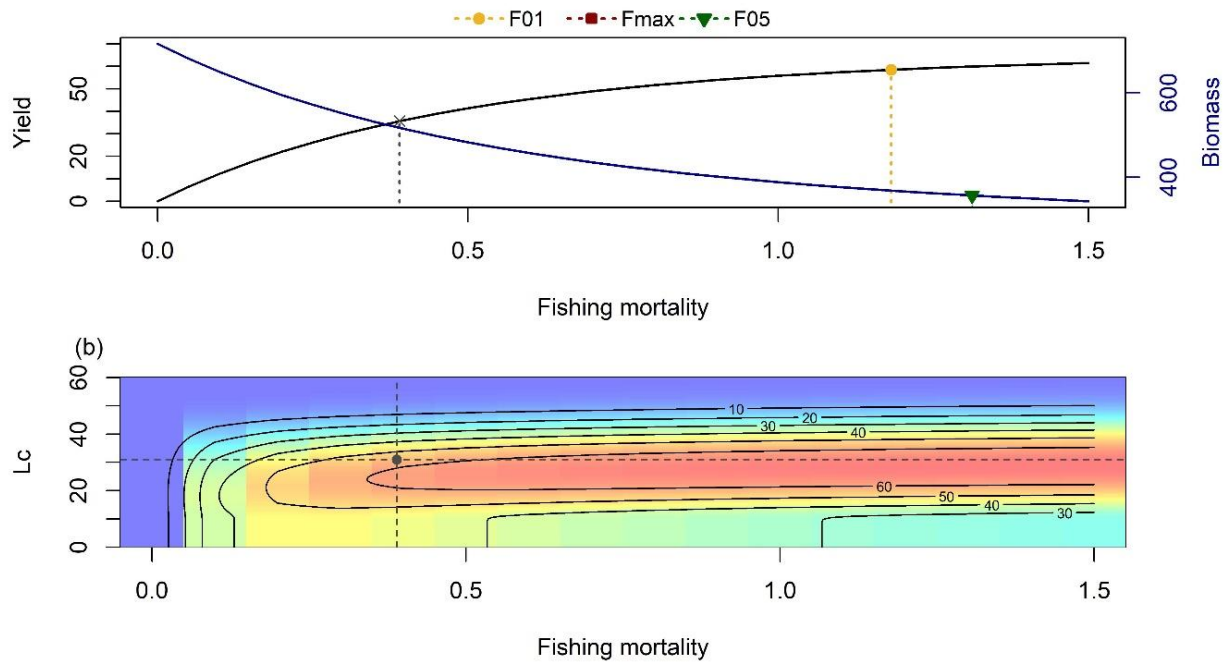
curr.B (tonnes)	Current biomass, estimated weight of the living fish population at the time of assessment.	97209.29	516.61
curr.Lc (mm)	Length at first capture or recruitment to the fishing gear.	27.5	31

**Size at first capture and age at 0.5 probability of capture%.**

The observed average size at first capture ( $L_c$ ) for *B. nurse* (27.5 mm SL; 6.3-11) and *E. bredoi* (30.5 mm SL; 6.3-12) are below the species' observed  $L_{50}$  (see Figure 6.3-1 & Figure 6.3-2). The age at 50% probability capture ( $t_{50}$ ) was observed at 2.2 months for *B. nurse* and 6.5 months for *E. bredoi*, suggesting that *B. nurse* becomes vulnerable to fishing mortality at a relatively small size and age, compared to *E. bredoi*.



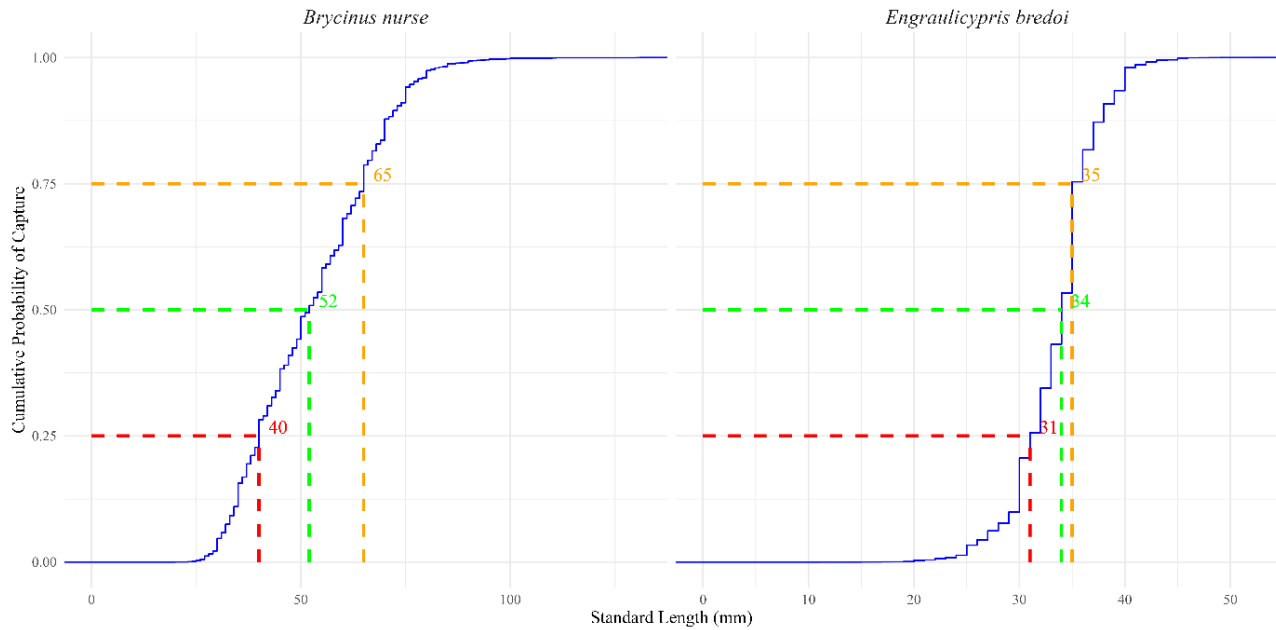
**Figure 6.3-11.** Estimated yield-per-recruit (YPR), biomass-per-recruit (BPR), fishing mortality rates (F01, F05, Fmax), and length at first capture ( $L_c$ ) for *Brycinus nurse* in Lake Albert, based on length-frequency data collected between February 2021 and June 2022.



**Figure 6.3-12.** Analysis of yield-per-recruit (YPR), biomass-per-recruit (BPR), fishing mortality rates (F01, F05, Fmax), and length at first capture (Lc) for *Engraulicypris bredoii* in Lake Albert, based on length-frequency data, collected between February 2021 and June 2022.

**Probability of capture at 25%, 50%, and 75%.**

The probability of capture analysis (**Figure** ) revealed distinct selectivity patterns for *Brycinus nurse* and *Engraulicypris bredoii*. For *B. nurse*, the length at 50% probability of capture ( $L_{c50}$ ) was estimated at 52 mm, with 25% and 75% capture probabilities at 40 mm and 65 mm, respectively. In *E. bredoii*,  $L_{c50}$  occurred at 34 mm, with corresponding 25% and 75% capture probabilities at 31 mm and 35 mm, respectively. The selection curve for *E. bredoii* is steep, indicating a narrow selection range, while that of *B. nurse* is broader, with a wider span across length classes.



**Figure 6.3-13.** Comparative analysis of length (mm) at 25%, 50%, and 75% probability of capture for *Engraulicypris bredoi* and *Brycinus nurse* in Lake Albert, estimated from VPA, using length-frequency data collected between February 2021 and June 2022.

## 6.4. DISCUSSION

The life-history traits exhibited by *Brycinus nurse* and *Engraulicypris bredoi* in Lake Albert, such as sex ratio, size at maturity, population size structure, length–weight relationships, and condition factor, have critical implications for the sustainable management of these economically and ecologically important species. These traits not only reflect the adaptive strategies of the species to their environment but also reveal the effects of fishing pressure and habitat disturbances on their populations.

### Sex ratios and selective fishing pressures

The transition in the sex ratio of *B. nurse* from a previously reported female-dominated population (2:1) (Namulemo et al., 2008) to a current male-biased ratio (2:1) is a concerning indicator of selective fishing mortality. This shift may be attributed to sex-specific behaviors and morphological characteristics that make larger, fecund females more vulnerable to capture (Bunnefeld et al., 2009; Marealle et al., 2010). Additionally, environmental stressors and climate-driven changes can influence sex differentiation and mortality patterns (Sørdalen et al., 2018; Jury et al., 2019; Geffroy &

Wedekind, 2020). Such imbalances can compromise genetic diversity, reduce reproductive potential (Ogburn, 2019), and ultimately heighten the risk of population collapse (Wedekind, 2012). The larger size at sexual maturity observed in female *B. nurse* further supports the hypothesis of size- and sex-selective exploitation.

### **Size at maturity and habitat connectivity**

Size at maturity is a fundamental parameter for effective fisheries regulation and conservation (Schill et al., 2010; Gwinn et al., 2015; Ahrens et al., 2020; Piferrer & Anastasiadi, 2023). The stability in size at maturity over time for *B. nurse* (Namulemo et al., 2008), coupled with its observed spatial variation, suggests possible migratory behavior and reliance on specific habitats for reproduction. This finding underscores the importance of habitat heterogeneity in supporting breeding and recruitment processes (Riede, 2004; Groves et al., 2022). Previous studies on Lake Albert (Wandera & Balirwa, 2010; NEMA, 2012; NELSAP, 2019) similarly emphasize the critical role of wetlands, shallow inshore habitats, and riverine inlets in facilitating life-cycle completion for *B. nurse*. Therefore, the protection and restoration of these habitats are essential components of fisheries management.

A particularly unique observation is the reversed pattern of maturation in *E. bredoi*, where males attain sexual maturity at a larger size than females. This contrasts with patterns commonly reported for many teleost species, where females often mature at equal or larger sizes than males, though this is not universal and is strongly species-specific (Magellan & Magurran, 2009). Male-biased size at maturity has been documented in species with pronounced sexual competition or mating systems that favor larger males, such as the corkwing wrasse (*Symphodus melops*) (Halvorsen et al., 2016), bluehead wrasse (*Thalassoma bifasciatum*) (Warner, 1984), and guppies (*Poecilia reticulata*) (Reynolds & Gross, 1992; Pitcher & Evans, 2004). In *E. bredoi*, this pattern may confer reproductive advantages to larger males through enhanced mating success or dominance, while also potentially reflecting differential fishing pressure between sexes. The presence of mature individuals throughout the year, with a peak in June, supports a strategy of near-continuous reproduction. Management measures should therefore consider protection during peak breeding periods, for example through seasonal or temporal fishing restrictions.

## **Population structure and exploitation patterns**

Understanding population size structure provides valuable insights into recruitment dynamics, growth trajectories, and mortality rates, particularly in heavily exploited systems (Froese et al., 2008; Neumann & Allen, 2012). In this study, *B. nurse* exhibited a tri-modal length distribution, indicative of multiple cohorts or spawning events throughout the year, a trait common in r-strategist species (Paloheimo & Chen, 1996; Haddon, 2011). Conversely, *E. bredoi* showed a more uniform size distribution, consistent with continuous recruitment. These differences underscore the importance of incorporating species-specific dynamics into stock assessment models and management frameworks (Kolding et al., 2016; Gebremedhin et al., 2021).

Disparities in mean fish length between catches obtained using experimental gears (8-mm mesh) and those from artisanal fisheries (predominantly 5-mm mesh) clearly reflect non-compliance with the existing mesh size regulations for Lake Albert (Fish (Fishing) Rules, 2010). The 8-mm mesh used in the experimental sampling corresponds to the recommended minimum mesh size for the small pelagic fishery on the lake, whereas the commercial artisanal fleets largely operate with 5-mm meshes that are below the legal threshold (NaFIRRI, 2021). Consequently, artisanal catches are dominated by immature individuals, indicating growth overfishing driven by weak enforcement of the few existing gear regulations. This persistent use of undersized meshes undermines recruitment, compromises stock replenishment, and threatens long-term sustainability of the small pelagic fishery. Strengthening monitoring, control and surveillance, alongside community-based compliance and co-management mechanisms, is therefore critical to improve adherence to mesh size regulations and safeguard future yields.

## **Length–weight relationships and condition factor as health indicators**

Length–weight relationships and condition factors (K) are vital indicators of fish health, reproductive status, and habitat quality (Le Cren, 1951; Gupta & Tripathi, 2017; Mnemba et al., 2022). In this study, both species exhibited positive allometric growth ( $b > 3$ ), indicating an increase in body mass disproportionately higher than length, often associated with good feeding conditions and environmental suitability (Olopade et al., 2020; Muhammad et al., 2017). Notably, *B. nurse* demonstrated a higher condition factor compared to *E. bredoi*, suggesting better overall physiological status and possibly greater reproductive success (Sarkar et al., 2013; Ferdaushy & Alam, 2015). This may also reflect species-specific differences in growth strategies and ecological niches.

Variability in condition factor among sexes within species may indicate differences in reproductive investment or energy allocation (Imam et al., 2010; Roul et al., 2020). This metric, therefore, serves as an important tool for monitoring not only individual species health but also broader ecosystem trends and anthropogenic impacts (Cavraro et al., 2019). Regular assessment of condition indices can provide early warnings of overexploitation, declining food availability, or habitat degradation.

The analysis of growth parameters demonstrates that *E. bredoi* and *B. nurse* in Lake Albert are characterized by divergent life-history strategies that influence their vulnerability to fishing pressure. *E. bredoi* grows faster, matures earlier, and has a shorter lifespan, traits typical of r-strategists (Winemiller & Rose, 1992; King & McFarlane, 2003). Conversely, *B. nurse* exhibits a more K-selected strategy, growing slower and living longer, making it inherently more susceptible to recruitment overfishing if heavily exploited (Froese et al., 2021).

The relatively high estimated values of theoretical age at zero length ( $t_0 = 0.63$  years for *B. nurse* and 0.35 years for *E. bredoi*) likely reflect limitations inherent in length-frequency-based growth estimation rather than true biological ages at length. For small, fast-growing pelagic species, sparse representation of early life stages in the catch and gear selectivity against very small individuals can bias ELEFAN-based fitting, leading to inflated  $t_0$  estimates. Consequently,  $t_0$  was treated as a model-fitting parameter to improve growth curve alignment, while biological interpretation and management inferences were based primarily on more robust parameters such as  $L_\infty$ ,  $K$ , and derived reference points.

The current exploitation rates ( $E = 0.59$  for *E. bredoi* and 0.64 for *B. nurse*) remain below the estimated biological reference points, with *E. bredoi* having  $E_{0.1} = 1.78$ ,  $E_{0.5} = 1.91$  and  $E_{\max} = 7.54$ , and *B. nurse* having  $E_{0.1} = 1.63$ ,  $E_{0.5} = 0.96$  and  $E_{\max} = 2.37$ , indicating that both stocks are not yet overexploited. However, the proximity of current fishing mortality to  $F_{0.5}$  for *B. nurse* ( $F = 0.29 \text{ year}^{-1}$  versus  $F_{0.5} = 0.43 \text{ year}^{-1}$ ), coupled with a relatively low biomass per recruit at  $F_{\max}$  (331.63 g), suggests that this species is approaching its biological limit of sustainable exploitation.

For *E. bredoi*, although the species is characterized by small body size and rapid population turnover, which can increase vulnerability to environmental stressors and gear selectivity, particularly where immature fish are harvested, these same life-history traits also confer a relatively high capacity

for rapid population recovery when fishing pressure is reduced or effectively managed (Pauly et al., 2021; Gayanilo & Pauly, 1997).

The low length at first capture ( $L_c = 30.5$  mm) for *E. bredoi* compared to its asymptotic length (52.20 mm) and  $L_{50}$  (31.5 mm) suggests premature capture, which undermines stock productivity and spawning potential. Increasing  $L_c$  through mesh size regulation would improve YPR and BPR, enhancing stock resilience (Froese, 2004). Similarly, the current YPR for *B. nurse* (4879.24 g at  $F_{0.1}$ ) compared to its potential YPR at  $F_{max}$  (5086.14 g) indicates that limited yield gains are possible through higher fishing pressure, reinforcing the prudence of adopting precautionary approaches around  $F_{0.1}$  and  $F_{0.5}$ .

The estimated length at 50% capture for both species suggests premature harvesting relative to their biological maturity, with potential long-term impacts on stock productivity and sustainability. For *E. bredoi*, the  $L_{c50}$  (34 mm) exceeds the estimated size at 50% maturity for males (31.5 mm). Similarly, *B. nurse* is captured at a mean  $L_{c50}$  of 52 mm, which is well below the estimated 50% maturity size for females (61 mm), although male maturity occurs earlier. These findings imply that a significant portion of individuals are being removed from the population before they have had the chance to spawn at least once, a situation known to compromise the spawning potential and lead to recruitment overfishing (Froese et al., 2016; Cope & Punt, 2009). From a stock assessment perspective, this early capture reduces both yield-per-recruit and biomass-per-recruit potential. For instance, fishing at or above current exploitation levels ( $E = 0.64$  for *B. nurse*;  $0.59$  for *E. bredoi*) without protective measures could exacerbate declines in spawning biomass, as reflected in the relatively low BPR values at  $F_{max}$  compared to  $F_{0.5}$  for both species. This suggests that current fishing practices are operating close to or beyond biologically optimal exploitation levels, especially given the short life span of *E. bredoi* and its fast growth dynamics.

### **Life-history implications and transboundary considerations**

The life-history analysis of *Brycinus nurse* and *Engraulicypris bredoi* revealed key traits influencing their vulnerability to light-assisted fishing, particularly the early capture of immature individuals relative to their size at 50% maturity. While the study generated robust data for the Ugandan side of Lake Albert, it is important to recognize that Lake Albert is a transboundary resource, with differing fishing regulations on the DRC side where light fishing is prohibited (*personal*

*communication*). These regulatory differences may result in spatial variation in population structure, growth patterns, and stock resilience, underscoring the importance of coordinated transboundary resource monitoring and management. Integrating life-history information with cross-border assessments can provide a more accurate basis for establishing recruitment-sensitive reference points and harmonized management measures for the shared SPS stocks.

## **6.5. CONCLUSION AND RECOMMENDATIONS:**

### **6.5.1. Conclusion**

This study provides critical insights into the life-history traits, population dynamics, and exploitation patterns of *Brycinus nurse* and *Engraulicypris bredoi* in Lake Albert, contributing valuable knowledge towards the sustainable management of small pelagic fisheries. The overall findings indicate generally healthy but vulnerable stocks, with significant intra- and interspecific differences in biological parameters across habitats. Distinct variation was observed in size at 50% maturity, length–weight relationships, condition factors, and population structures, hallmarks of species-specific growth and reproductive strategies shaped by ecological and fishery-driven pressures.

A particularly unique finding was the reversed maturation trend in *E. bredoi*, where males attained 50% maturity at a larger size than females, an unusual deviation from the typical teleost pattern. This could imply complex social structuring, density-dependent maturation, or sex-specific growth strategies, warranting further ecological and reproductive behavioral studies. Additionally, the observed shift in *B. nurse* sex ratio from female- to male-dominated cohorts, especially in larger size classes, strongly suggests selective removal of larger, mature females, likely a result of prolonged exploitation with non-selective gears. This has potential implications for spawning biomass and recruitment, particularly for longer-lived, slow-growing species like *B. nurse*.

The observed year-round breeding patterns for both species, with seasonal peaks in *E. bredoi* (June) and *B. nurse* (February–March), underscore their resilience and adaptability to Lake Albert's dynamic environmental conditions. However, such reproductive flexibility can be undermined by persistent fishing pressure on immature individuals, as revealed by the widespread use of illegal mesh sizes and the absence of effective regulatory enforcement.

Furthermore, the tri-modal size distribution in *B. nurse* suggests the existence of discrete cohorts or sub-populations, possibly driven by spatial or temporal spawning segregation, whereas *E. bredoi* exhibited a more uniform size structure, consistent with continuous recruitment and faster life-

history turnover. These findings emphasize the need to consider species-specific population structures and reproductive strategies when designing management interventions.

In conclusion, while the populations of *B. nurse* and *E. bredoi* in Lake Albert show signs of biological resilience, continued overexploitation, particularly of juveniles, poses a long-term threat to their sustainability. Strengthened enforcement of gear regulations, habitat protection, coordinated cross-border governance, and the integration of scientific and local knowledge are essential to safeguard these critical fishery resources and the livelihoods they support.

### **6.5.2. Recommendations**

From a management perspective, the study recommends the following measures to ensure the long-term sustainability of both small pelagic species and large-bodied fish stocks in Lake Albert:

1. Increase size at first capture through gear regulation: Increase mesh size limits to raise the length at first capture ( $L_c$ ) above the size at 50% maturity for *B. nurse*, to ensure adequate recruitment and reproductive contribution prior to harvest.
2. Protect critical habitats and juvenile zones: Prioritize inshore nursery and breeding areas for protection of spawning stocks.
3. Strengthen cross-border and community collaboration: Harmonize fisheries management policies between Uganda and DRC, and integrate local ecological knowledge from fishers into management planning, particularly for identifying and safeguarding breeding sites and seasons.
4. Establish a long-term monitoring and research framework: Institutionalize continuous ecosystem-based monitoring of life-history traits and population dynamics using advanced technologies, including molecular tools for maturity and aging assessments, to inform adaptive and responsive management.

These recommendations are consistent with global guidance advocating ecosystem-based fisheries management and precautionary reference points in tropical lake systems (FAO, 2020; Lorenzen et al., 2021).

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## CHAPTER SEVEN

### **EFFECTS OF ARTIFICIAL LIGHT CONFIGURATIONS AND GEAR SPECIFICATIONS ON THE CATCH RATES (CPUE), SIZE STRUCTURE, AND RECRUITMENT PATTERNS OF TARGET SPECIES (ENGRAULICYPRIS BREDOI AND BRYCINUS NURSE) AND NON-TARGET SPECIES IN LAKE ALBERT.**

#### **CONTEXT**

This chapter investigates the technical drivers of productivity and inter-fishery conflict, focusing on artificial light types and net-panel configurations. The rapid expansion of light-based fisheries has sparked social tensions, as traditional demersal fishers perceive SPS gear as a threat to large-bodied stocks. Through experimental fishing, the study identifies a "technical optimum" of eight net panels, reaching a vertical depth of 16 meters, which maximizes SPS yields. Deploying gear beyond this depth does not significantly increase target catch but leads to an exponential rise in the bycatch of juvenile high-value species like Nile perch. Furthermore, the research compares light sources, finding that solar-LED lights provide superior catch efficiency and safety compared to traditional kerosene lamps. The management implication is clear: standardizing gear to an eight-panel limit can protect demersal nurseries and mitigate user-group conflicts by reducing the "vacuum effect" of deep-set pelagic nets.

The detailed chapter is presented as a published manuscript under the title "Effects of artificial illumination and net panel configurations on small pelagic fisheries and bycatch on Lake Albert, East Africa. *Journal of Great Lakes Research*, 102690 (10.1016/j.jglr.2025.102690)."



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## Effects of artificial illumination and net panel configurations on small pelagic fisheries and bycatch on Lake Albert, East Africa

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### ABSTRACT

Small pelagic fisheries are crucial for socio-economic development, yet their sustainable management in multi-species ecosystems like Lake Albert is challenged by user conflicts, particularly between pelagic and demersal fishers. These tensions are largely fueled by unverified perceptions surrounding the ecological impacts of light-based small pelagic species (SPS) fisheries, including bycatch and net-panel configurations. This study provides empirical evidence to inform management decisions that support coexistence within the lake's multi-species fishery. We examined the effects of light type, intensity, and net stacking on catch rates of *Engraulicypris breddoi* and *Brycinus nurse* (belonging to orders Cypriniformes and Characiformes, respectively, and known locally as muziri and rogoogi), as well as the bycatch of economically important large-bodied species. Using kerosene lanterns and solar lights at varying intensities and net configurations, *E. breddoi* showed consistently higher catch rates (4.5–10 kg/net-haul/day) than *B. nurse* (2.5–5 kg/net-haul/day), with no significant differences across light types. Solar lights, however, enabled higher nightly catches due to increased operational efficiency. Bycatch, predominantly juvenile Nile perch (*Lates niloticus*), was significantly higher in shallow inshore habitats and increased with net stacking, from < 0.5 kg/boat/day (six panels) to 15 kg/boat/day (15 panels). These results highlight the need to regulate net-panel stacking and implement spatial strategies that shift SPS fishing offshore, protecting inshore nursery habitats. We recommend revising regulations to limit fishing depth to 16 m, promote solar light use, and establish long-term monitoring to support balanced and sustainable management.

### 1. Introduction

Small pelagic fisheries contribute one-third of inland capture fish production globally (FAO, 2022), and approximately 70 % in many African Great Lakes (Kolding et al., 2019). These fisheries are vital for global food protein supply, employment, and animal feed production (Bórquez and Hernández, 2009; Isaacs, 2016; Tacon and Metian, 2009a, 2009b). They are particularly important for riparian communities in developing countries due to their high abundance and affordability (Sekadende et al., 2020). Given their significance, understanding the ecology of small pelagic species and the impacts of fishing gear is crucial for making informed, sustainable management decisions in multi-

species ecosystems.

Lake Albert supports a multi-species-based fishery (Mbabazi et al., 2012, 2019; NaFIRRI, 2012; NELGAP, 2019), characterized by a variety of harvestable species with diverse adult sizes (Nakiyende et al., 2013, 2023; Wandera and Balirwa, 2010), necessitating the use of multiple gear types. However, management is complicated by ongoing socio-economic conflicts between pelagic and demersal fishing clusters (NaFIRRI, 2012; Nakiyende et al., 2023). These conflicts are largely driven by unverified perceptions regarding the ecological impacts of light-based small pelagic species (SPS) fishing practices, particularly with respect to juvenile bycatch and the effects of light type, intensity, and net panel configurations.

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Fisheries bycatch is a globally recognized threat to both marine and freshwater ecosystems (Komoroske and Lewison, 2015; Lively and McKenzie, 2023; Raby et al., 2011), and addressing this persistent challenge remains particularly difficult in multi-species fisheries such as those of the SPS in Lake Albert and the African Great Lakes. In this study, bycatch is defined as the portion of the catch comprising large-bodied fish species that are incidentally retained as juveniles in SPS harvesting gear or methods, but are not the primary target of the fishery, whether they are ultimately retained or discarded (Alverson et al., 1994). While this general definition aligns with global fisheries science, our application was further informed by fishers' perceptions on Lake Albert. Fishers consistently considered bycatch to include large-bodied species of high commercial and ecological importance that are captured at juvenile stages in gears targeting SPS. These included *Lates niloticus* (Nile perch), *Alestes baremose* (pebbly fish), *Hydrocynus forskahlii* (elongate tigerfish), *Bogrus bajad* (Black Nile catfish), *Labeobarbus bynni* (Nile barb), *Ditrichodus niloticus* (Nile distichodus), and various *Tilapia* species, among others.

While it is inherently challenging to incorporate complex inter-species interactions into operational multi-species management models for multi-species fisheries (Skern-Mauritzen et al., 2016; Zhou et al., 2019), effective management of ecosystems like Lake Albert requires integrating socio-ecological considerations and assessing gear impacts (Powler, 1999; Purcell and Pomeroy, 2015). Despite data limitations common in small-scale fisheries, strategies to mitigate conflict, manage bycatch, and optimize fishing practices are essential (Haddon, 2011; Hins, et al., 2012). Of particular concern is juvenile bycatch, defined here as the incidental capture of economically and ecologically important juvenile, which contribute directly to stakeholder conflict. This conflict is especially pronounced between the large-species (demersal) fishers and SPS light-based fishers due to concerns over perceived excess bycatch of juvenile Nile perch and other large-bodied species. These concerns have even led to an unjustified ban, posing a challenge to managers in the absence of scientific guidance on mitigation the multi-species multi-gear fishery.

Traditionally, fisheries management on Lake Albert and other East African lakes has relied on gear-size-based management regulations, primarily aiming to protect juvenile and large fecund individuals by allowing them to reach sexual maturity and optimal size before harvest (Government of Uganda, 2010). This approach seeks to prevent growth overfishing and ensure reproductive sustainability (Carvalho and Humphries, 2022; Cinner et al., 2009). However, gear-size regulations alone often overlook key ecosystem dynamics and fishing effort. Growing evidence suggests that such strategies neither maximize fishery yields nor sufficiently reduce ecological impacts (Garcia et al., 2012; Mpomwenda et al., 2023; Nyamweya et al., 2023).

Balanced harvest approaches, advocating for proportional harvesting across species and size classes, offers a promising pathway to reduce ecosystem-level fishing impacts, including bycatch (Kolding and van Zwieten, 2014; Zhou et al., 2019). However, adoption of such approaches in gear-size-regulated systems like Lake Albert remains limited, hindered by entrenched mindset and rigid legal frameworks (Natugonza et al., 2022). Effective management of complex, multi-species fisheries requires an integrated approach, one that combines gear selectivity, input (effort) controls, and ecological considerations. This would not only address interspecies interactions and resource-use conflicts but also support ecological integrity and equitable socio-economic outcomes for fishing communities.

In Uganda's waters of Lake Albert, light-based fisheries actively target two SPS: the cypriniform *Engraulicypris bredoi* (known locally as musiri) and characiform *Brycinus nana* (nurse tetra or ragoogi locally). From the early 2000 s to 2020, this fishery expanded significantly, reflected in rising numbers of boats, fishers, nets, lights, and light sources (Mbabazi et al., 2012; NaFIRRI, 2012; Nakiyende et al., 2023). This growth is likely attributed to gear efficiency and improved SPS catches, coinciding with a documented decline in the contribution of large

species to total annual catches (Mbabazi et al., 2012, 2019; Nakiyende et al., 2023). Initially, fishers used 3–4 kerosene lamps per boat, with one lamp per raft. With the introduction of solar lighting, the number of bulbs increased dramatically, now ranging from 9 to 21 bulbs per boat, or about three bulbs per raft.

Despite the widespread adoption of SPS light-based fishing technologies across Ugandan waters, including Lakes Albert, Victoria, and Kyoga (Lvfo, 2020, 2022; NaFIRRI, 2012; Nakiyende et al., 2023; LVFO, 2019; NaFIRRI, 2023), these technologies face opposition, particularly from stakeholders fishing for Nile perch and other large-bodied species. Concerns centre around the perceived impacts of light fishing on the sustainability of large-bodied species (NaFIRRI, 2012; Nakiyende et al., 2023). In response and acknowledging the economic importance of the Nile perch fishery in Uganda and East African Community, the minister responsible for fisheries issued a directive banning the use of stacked encircling nets (locally known as "Hurry-up" due to the speedy actions during hauling operations) and solar lights for SPS fishing (Africa-Press, 2024; Harvest Money, 2024a; Monitor, 2024; The Cooperator News, 2024; Uganda Radio Network, 2006). This ban, implemented by the Fisheries Protection Unit (FPU), was enacted as a precautionary measure but lacked scientific justification. Some boats continue to covertly deploy the prohibited gears, which are often confiscated and destroyed, and the fishers apprehended.

Unlike the Nile perch fishery, which is governed by established harvesting technology guidelines and regulations (Government of Uganda, 2010), the SPS light-based fishery lacks a specific regulatory framework to ensure sustainability of targeted stocks and the broader lake ecosystem. The ecological effects of SPS fishing technologies remain inadequately understood. Beyond effort and catch data comprehensive assessments of broader ecosystem impacts, such as juvenile bycatch of high-value large species, trophic disruptions from mass SPS removal, habitat disturbance, and biodiversity changes are lacking. This knowledge gap hampers science-based management that balances SPS fishery benefits with ecosystem sustainability (FAO, 1995). While studies from other regions highlight advantages of light fishing, such as improved efficiency and catch rates (Mgana et al., 2019; Nguyen and Winger, 2019; Solomon and Ahmed, 2016), they also report potential drawbacks, including increased bycatch, disruption of natural fish behaviour, and localized overfishing (Bassi et al., 2022).

To address critical data gaps, this study assessed the impacts of light-based SPS fishing on catch composition, juvenile bycatch, and fishing efficiency in Uganda's sector of Lake Albert. By integrating fishery-dependent (LVFO, 2019; Trimble and Berkes, 2013) and fishery-independent methods (Cashion et al., 2018; LVFO, 2007; Nielsen, 2018; Yang et al., 2022), we examined how light type, intensity, and vertical net stacking (panelling) influence both target SPS and incidentally captured large-bodied species. The study provides evidence-based insights to guide equitable SPS fishery management, moving beyond perception-driven policies towards ecosystem-based fisheries management. These findings are crucial for strengthening regulatory frameworks and mitigating fishing conflicts within Lake Albert and other African Great Lakes.

## 2. Materials and methods

### 2.1. Study area and sampling approach

Controlled experimental fishing surveys (LVFO, 2007) and catch assessment surveys (LVFO, 2019) for SPS were conducted in the Ugandan sector of Lake Albert at four selected fishing sites and six landing sites, respectively (Fig. 1). Site selection was guided by the need to represent the lake's diverse habitats, categorized into shallow inshore ( $\leq 10$  m deep,  $< 500$  m offshore) and deep open ( $\geq 20$  m deep, 1000–2000 m offshore) habitats, following lake bathymetry characterization by Hamilton et al. (2022). Additional criteria for selection included the presence of active light fishing throughout lunar cycles,

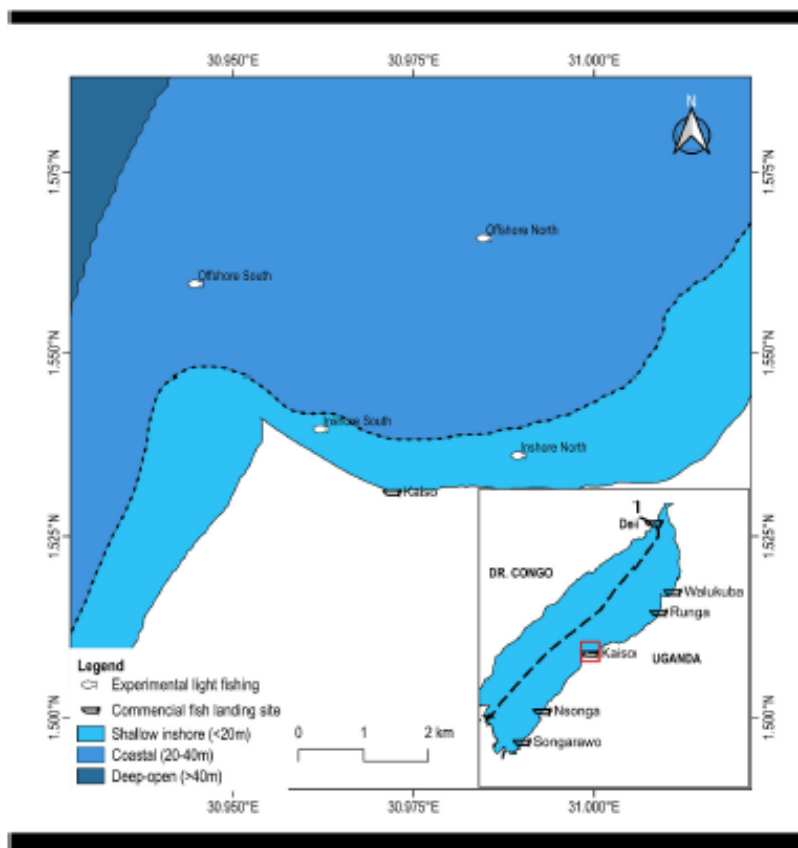


Fig. 1. Locations of sampled sites for experimental and commercial catch data on Lake Albert, Uganda. The inset map indicates landing sites where commercial catch data were collected, while the zoomed area illustrates the experimental sampling sites.

accessibility, cooperation from local fishers, and adherence to security advisories and safety protocols issued by the FPU. To complement data from experimental and commercial catches, stakeholder perceptions regarding bycatch composition in SPG fisheries were collected through a structured questionnaire (Electronic Supplementary Material (ESM) Appendix S1). This approach enhanced the study's comprehensiveness by integrating both empirical and experimental insights, enabling a robust assessment of the potential ecological and socio-economic impacts of light fishing practices.

## 2.2. Data collection

### 2.2.1. Experimental fishing surveys

Experimental fishing was conducted from February 2021 to June 2022 across four sampling stations (Fig. 1) to evaluate effects of artificial light type and intensity on catch rates of *E. bredoii*, *E. muriei*, and associated bycatch species. Three light types were tested: kerosene pressure lanterns (KPL), direct solar-powered LED bulbs (SPB-S), and battery-powered solar LED bulbs (SPB-M). SPB-S treatments were tested at intensities of 175, 275, 300, and 375 lm (ESM Fig. S1), while KPL and SPB-M setups ranged from one to four light units (lanterna/bulbo). SPB-S lights were charged directly from solar panels ashore and disconnected before deployment, while SPB-M bulbs relied on pre-charged batteries. All solar LED bulbs used in this study were supplied by Africa Power Limited (Kua Solar) (<http://www.africapowerltd.com/our-products>).

Monthly experiments were timed to coincide with the new moon

phase or dark nights (a period of peak light fishing activity) to ensure optimal darkness for night fishing observations. Sampling occurred for 2 days at each of the four sites over a 12-month period (excluding the months of January, March, and June 2021 missed due to adverse weather conditions), following standard protocols for biological surveys on Lake Victoria (LVPO, 2007). The missed months were re-sampled in 2022.

Fishing was conducted using an 8-panel, 8-mm mesh small-seine net ("lampala net"), with each panel measuring 2 m in depth and 100 m in length (ESM Fig. S2). The 8-mm mesh size was used because it is the only legally permissible size for small-seine nets on Lake Albert (Government of Uganda, 2010). Nets of 2 m × 100 m dimensions are also the most widely available and commonly used by artisanal fishers on Lake Albert and across other regional water bodies, including Lakes Victoria and Kyoga (LVPO, 2022). The use of eight net panels was further guided by a temporary advisory from the Fisheries Protection Unit (FPU), which recommended panel limits as a precautionary measure to regulate netting effort on Lake Albert. Light sources were mounted on floating rafts to attract fish, after which the net was used to encircle and concentrate the fish (ESM Fig. S3) for harvesting (Ben-Yami, 1976; Marchesan et al., 2005; Solomon and Ahmed, 2016). Each night of sampling included up to three hauls per light setup, with each haul separated by a 3-hour interval. All fishing experiments were performed using a motorized flat-transomed vessel, commonly known to as "oosee flat-at-one-end." Site-specific data, including depth, was also recorded during the surveys. A summary of the experimental survey sampling design is presented in Table 1.

**Table 1**  
Summary of experimental fishing survey sampling design.

Parameter	Description
Sampling period	February 2021 – June 2022
Total number of months sampled	12 (overlapping two calendar years)
Number of sites	Four (two inshore and two offshore)
Sampling frequency per site	Two days per month
Number of fishing hauls per setup	Up to three net hauls per night
Number of light types tested	Three light type or sources (KPI, SPB-S, SPB-M)
Dimensions of net used	8-panel small-seine net (2 m × 100 m/panel)

### 2.2.2. Catch assessment surveys (CASs)

#### Sampling design

CASs were conducted at six landing sites with active light-based SPS fisheries: Dei and Walukuba (North), Runga and Kaiso (Central), and Noonga and Gongarau (South) (Fig. 1). These sites were selected based on previous observations of mixed SPS catches (comprising *E. bredoii* and *B. nurse*) obtained using light attraction methods (Mbabazi et al., 2012; NaFIRRI, 2021).

Monthly CASs were conducted over a 24-month period between September 2019 and August 2022. At each landing site, trained community-based enumerators collected data on fish catches during two consecutive days in each of the four lunar phases (new moon (N), first quarter (Q), full moon (F), and third quarter (T)) per month, following LVPO (2019) standard operating procedures. A lunar calendar (<https://www.moongiant.com/calendar/>) was shared with the enumerator to ensure synchronization of sampling across all sites, under relatively similar environmental conditions.

Each day, up to 30 boats were randomly sampled upon their return from night fishing trips. Fishing typically started around 18:00–19:00 h and lasted for up to 12 h. Catch data were recorded for species composition, gear used, light type, and catch quantities. The use of community-based enumerators enabled capacity building and reduced overall costs associated with fishery-dependent data acquisition. The researchers maintained regular communication with field enumerators and conducted monthly visits to each landing site, to ensure strict adherence to sampling procedures. Additionally, a WhatsApp group was established to facilitate real-time coordination, allowing for the sharing of experiences and the prompt resolution of data collection challenges. A summary of the CAS sampling design is presented in Table 2.

#### Processing of catch

Processing of catch for both experimental and commercial catch data followed a similar procedure as described below:

- i. As mentioned in the background section, bycatch in this study was defined as large-bodied fish species (including *L. niloticus*, *A. baremose*, *H. forskahlii*, *B. bajad*, *L. bynni*, *D. niloticus*) incidentally retained in SPS fisheries, primarily as juveniles, although they are not the target of the fishery. From each sampled boat or haul, individuals of these large-bodied species were sorted and identified to species level.

**Table 2**  
Summary of catch assessment survey (CAS) sampling design.

Parameter	Description
Sampling period	September 2019 – August 2022
Duration	24 months
Number of landing sites	Six
Sampling frequency per site	Two days per lunar phase (four phases/month)
Number of sampling days per month	Eight days per site
Boats sampled per day	Up to 30 boats per day
Enumerators	Two per site (local community-based)
Sampling method	Random boat sampling upon landing

- ii. For the common bycatch species, lengths were measured in addition to counts and weights to determine population structure and mean lengths. These were then compared with published estimates of length at 50 % maturity from earlier studies (e.g., Nakiyende et al., 2013; Nkalubo et al., 2018) to assess the extent of juvenile capture, which has been a central point of contention in the light-based SPS fishery.
- iii. The remaining catch of the target species (*E. bredoii* and *B. nurse*) and small individuals of the large-bodied bycatch species were weighed in buckets and recorded.
- iv. A random sub-sample of 1 kg was taken from the mixed catch and preserved in 5 % formalin to allow for detailed laboratory analysis, including species verification, species composition, and length-weight measurements, that could not be reliably conducted in the field. Each preserved sample was labelled with essential metadata, including date, station, GPS location, haul number, light type and intensity, and species type, to ensure traceability and facilitate subsequent analyses.
- v. All preserved samples were stored in airtight containers and transported to the laboratory for detailed analysis of species composition, length-weight relationships, and sexual maturity.
- vi. In the laboratory, each sample was emptied onto a perforated sieve and rinsed under running water to remove excess preservative (formalin). The samples were then sorted into species groups.
- vii. Both individual fish length at 1-mm intervals and weight in grams (g) were recorded, and individuals were thereafter grouped in respective size classes.
- viii. For the bycatch of large-bodied species, both the total weight and individual length of all fish specimens were recorded.

### 2.2.3. Determination of fishing depth relative to vertical net panel stacking

Artisanal SPS fishers on Lake Albert deploy stacked nets ranging from four to 20 panels (NaFIRRI, 2012; NaFIRRI, 2021; Nakiyende et al., 2023). To assess how stacking influences fishing depth, experimental fishing trials were conducted in deep offshore waters (approximately 20–40 m depth) using nets configured with 4–20 panels, increasing in increments of two (ESM Fig. S4). Each net configuration was with a DST TD (Data Storage Tag with Temperature Depth sensor), manufactured by STAR-ODDI, attached to the footrope. These devices recorded temperature and depth data continually during fishing operations. After each haul, the device was detached, data downloaded, and then reattached for the next deployment. Three hauls were conducted per net configuration, and the average maximum depth reached by each configuration was calculated.

### 2.2.4. Determination of catch rates by stacked net panels

To ensure robustness of the findings, we integrated both experimental and artisanal catch data. The net stacking experiment served to precisely quantify the maximum fishing depth achieved by each configuration. Concurrently, data from catch assessments provided estimates of catch rates of the SPS, *E. bredoii* and *B. nurse*, alongside incidental bycatch of large-bodied species. Bycatch was first assessed by species composition and then pooled to be expressed as a proportion of the overall catch in subsequent computations. This integrated analytical approach delivered detailed insights into how net panel configurations influenced both target yield and bycatch composition.

### 2.2.5. Fishers' perceptions of bycatch in light-based small pelagic species fisheries

To complement experimental and artisanal catch assessments, and to provide a socio-ecological perspective on the impacts of the light-based SPS fishery, fishers' perceptions of bycatch were evaluated. Specifically, this assessment aimed to understand the species composition and relative contribution of non-target large-bodied species in catches, as perceived by the fishers themselves. Structured face-to-face interviews

were conducted at three landing sites: Dei, Kaiso, and Ntoroko (Fig. 1), using a standardized questionnaire. Respondents were randomly selected from fishers utilizing light attraction techniques.

For clarity and consistency, “bycatch” was defined as the portion of the catch comprising species not primarily targeted by SPG fishing gear, regardless of whether retained or discarded. Fishers were asked to:

- Indicate whether other species were landed as bycatch in SPG catch (Yes/No).
- Identify the most common bycatch species from a pre-specified list.
- Estimate the proportion of large-species bycatch in the light fisheries catch, selecting from predefined categories: < 5 %, 5–10 %, 10–20 %, 20–30 %, 30–50 %, or > 50 % (ESM Appendix 1).

These responses were analyzed to quantify the perceived contributions of primary target SPG and non-target large species (perceived as bycatch) in the fishery (Nakiyende et al., 2025). Perception-based estimates were then cross-referenced with experimental and artisanal catch assessment data to evaluate alignment between fisher’s observations and empirical measurements.

2.3. Data analysis

Experimental data were analyzed to evaluate the effects of light type and intensity on catch rates across different habitats. Artisanal (commercial) catch data were used to assess the impact of net panel stacking on catch rates of target and non-target species. Bycatch composition data from fisher perceptions, experimental catches, and artisanal catches were integrated to enable a comprehensive analysis across all data sources.

Catch per unit effort (CPUE), expressed in kilograms per hour fished (kg hour<sup>-1</sup>) was computed for each species, and compared across light types, light intensity (lumens/number of bulbs/lanterns), habitat type, and net panel configurations. A three-way analysis of variance (ANOVA) was used to evaluate differences in mean CPUE, followed by Tukey’s post-hoc test for pairwise comparison of specific differences between groups. Standardization procedures were applied to address any incomplete or missed hauls, ensuring the reliability and comparability of the results.

3. Results

3.1. Catch rates of *Engraulicypris bredoi* and *Brycinus nurse* across light types, intensities, and habitats

The catch rates of SPG (*E. bredoi* and *B. nurse*) across different habitats showed no significant difference with respect to light types and intensities ( $p > 0.05$ ; Table 3). However, significant differences were observed between control (fishing without light) and the three light types (KPL, SPB-M, and SPB-S). Specifically, catch rates were significantly lower in the control treatment for both *E. bredoi* ( $F = 7.0446$ ,  $DF = 3$ ,  $p \leq 0.001$ ) and *B. nurse* ( $F = 21.823$ ,  $DF = 3$ ,  $p \leq 0.001$ ) compared to all illuminated treatments (Table 3; Fig. 2). Additionally, a significant interaction between habitat type and light source was observed for *E. bredoi* ( $F = 13.8889$ ,  $DF = 3$ ,  $p \leq 0.001$ ). Post-hoc Tukey multiple comparison tests (at a 95 % family-wise confidence level) confirmed that catch rates in the control treatment differed significantly ( $p \leq 0.001$ ) from those under three artificial light types across both inshore and offshore habitats.

3.2. Bycatch composition in artisanal catches, experimental catches, and fisher perception data

Bycatch composition, expressed as the proportion of non-target species within the total catch, was evaluated from artisanal and experimental data sets, as well as from fishers’ perceptions (Fig. 3). *Engraulicypris bredoi* consistently dominated the SPG catch, followed by *B. nurse*, while the bycatch made up less than 10 % of the total catch across all sources (Fig. 3). Notably, large-bodied species bycatch was present across all lighting types (Fig. 3). The highest bycatch proportion (14.4 %) was recorded in artisanal catches landed using multiple solar bulbs (SPB-M), while the lowest (3.2 %) occurred under kerosene lanterns. Bycatch proportions for other light types were similar, all below 10 % (Fig. 3). It is important to note that artisanal and perception-based data included only fisheries using kerosene lanterns and SPB-M, as data were unavailable for fishing without lights (CTR) and for SPB-S (solar bulbs with a known luminous intensity in lumens).

3.3. Bycatch species composition across light types, intensities, and habitats

A total of 15 fish species were identified as bycatch in the experimental catch across different light types and intensities in both shallow inshore and deep offshore habitats (Fig. 4). The five most frequently encountered bycatch species were *Oreochromis niloticus* (Nile tilapia),

Table 3  
Analysis of variance (ANOVA) results showing the effects of habitat, light type, light intensity, and their interactions on catch rates of *Engraulicypris bredoi* and *Brycinus nurse* in Lake Albert, Uganda. Degrees of freedom (Df), sum of squares (Sum Sq), mean squares (Mean Sq), F-values (F value), p-values (Pr(>F)), and significance levels (Signif.) are provided. Significance codes: \*\*\*  $p < 0.001$ , \*\*  $p < 0.01$ , \*  $p < 0.05$ .

Species	Variable	Df	Sum Sq	Mean Sq	F value	Pr(>F)	Signif.
<i>Engraulicypris bredoi</i>	Habitat	1	188	187.97	2.3404	0.12664	
	Light type	3	1697	565.78	7.0446	0.00012	***
	Intensity	8	731	91.39	1.138	0.33578	
	Habitat: light type	3	3346	1115.47	13.8889	9.82E-09	***
	Habitat: intensity	8	894	111.74	1.3914	0.1973	
	Light type: intensity	5	254	50.82	0.6328	0.67483	
	Habitat: light type: intensity	3	134	44.82	0.5581	0.64291	
	Residuals	537	43,128	80.31			
	<i>Brycinus nurse</i>	Habitat	1	0.3	0.28	0.0171	0.896
Light type		3	1086.5	362.16	21.823	2.39E-13	***
Intensity		8	58.4	7.3	0.4396	0.8972	
Habitat: light type		3	27.8	9.25	0.5574	0.6434	
Habitat: intensity		8	61.1	7.63	0.46	0.8841	
Light type: intensity		5	135.4	27.09	1.6322	0.1496	
Habitat: light type: intensity		3	14	4.68	0.2817	0.8386	
Residuals		537	8911.7	16.6			

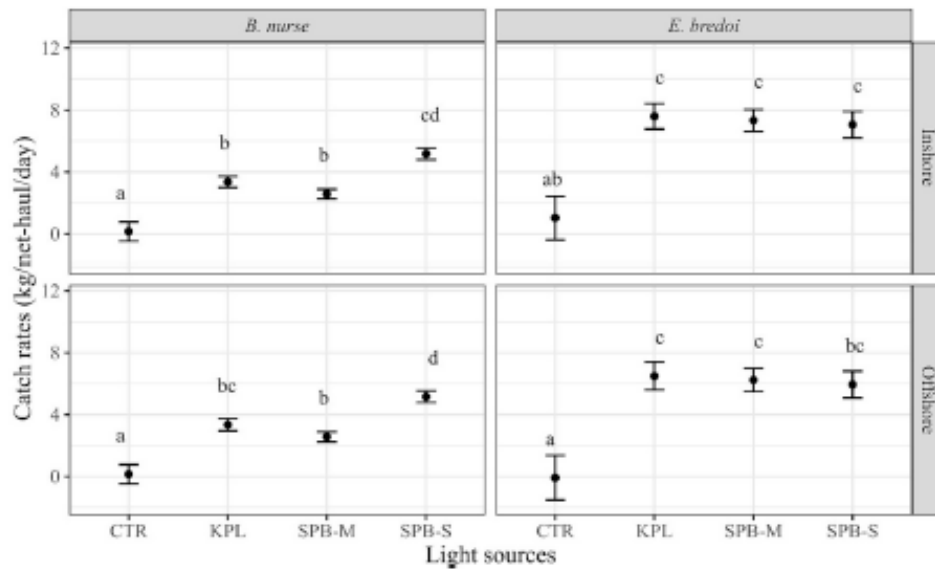


Fig. 2. Catch rates ( $\pm$  SE) of *Engraulicypris bredoi* and *Brycinus nurse* by light type on Lake Albert, Uganda. Light types include C – control (no light), KPL – kerosene-powered lanterns, SPB-M – multiple-unit solar bulbs, and SPB-S – single-unit solar bulbs. Letters on the bar indicate levels of significant differences. Different letter combination shows significant difference and same letter for two groups showed no significant differences.

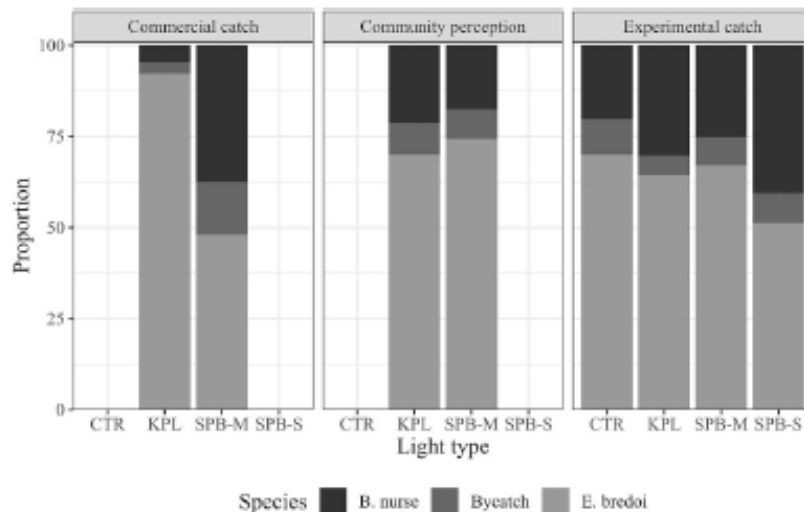


Fig. 3. Bycatch composition in the different light types based on community perceptions, commercial catch, and experimental data from Lake Albert, Uganda.

*L. niloticus*, *Hydrocynus forskahlii*, *Alestes baremose*, and *Ditichodus niloticus* (Fig. 4). Other bycatch species included *Malapterurus electricus* (electric catfish), *Labeo horie* (Asuan labeo), *Ctenopoma muriei* (ocelated labyrinth fish), *Bagrus bajad*, *Alestes macrolepidotus* (true big-scale tetra), and *Labeobarbus bynni*. Notably, bycatch quantities were higher in inshore habitats, where daily catches for species like *O. niloticus*, *L. niloticus*, and *H. forskahlii* reached 10–12.5 kg per day. In contrast, offshore catches of these dominant bycatch species barely exceeded 5 kg per day (Fig. 4). Across all light treatments and intensities, the majority of bycatch species were caught in quantities below 1 kg per day (Fig. 4).

### 3.4. Catch rates of *Engraulicypris bredoi* and *Brycinus nurse* across net panel configurations

A significant positive relationship was observed between net panel configuration and catch rates for *E. bredoi* and *B. nurse* in the artisanal light-based fishery ( $p < 0.001$ ). The highest catch rates for both species occurred at the 14th net panels (Fig. 5a), with mean daily catch rate ( $\pm$  standard error, SE) of  $235.0 \pm 3.66 \text{ kg boat}^{-1} \text{ day}^{-1}$  for *E. bredoi* and  $133.7 \pm 3.02 \text{ kg boat}^{-1} \text{ day}^{-1}$  for *B. nurse*. Specifically, *E. bredoi* catch rates increased steadily up to the 14th panel before declining, whereas *B. nurse* catch rates plateaued after the ninth panel, with subsequent additional panels yielding only marginal gains (Fig. 5a).

To evaluate efficiency and economic implications of increasing net panel numbers, especially in light of concerns about unregulated net

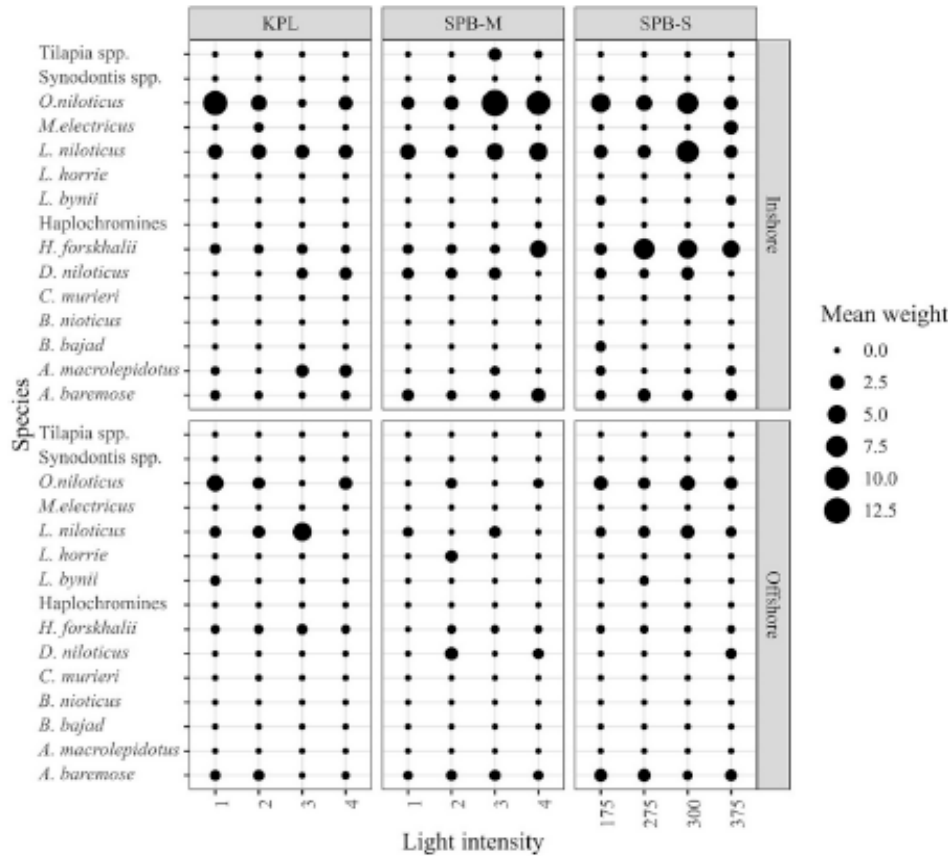


Fig. 4. Comparison of bycatch composition in experimental catches under varied light types and intensities within inshore and offshore habitats of Lake Albert, Uganda. SPB-M – multiple-unit solar bulbs, SPB-S – single-unit solar bulbs, and KPL – kerosene-powered lanterns. Light intensity for SPB-M and KPL is quantified by the number of bulbs and lamps, respectively, while SPB-S intensity is measured in lumens.

panel expansion and its contribution to bycatch, standardized catch rates (kg/net panel/day) were calculated by dividing the total catch by the number of panels (Fig. 5b). Results revealed an initial rise in catch per net panel (area), peaking at an optimal threshold before declining. Beyond this threshold, additional panels did not improve catch per unit area, indicating diminishing returns (Fig. 5b). For *E. breddoi* the standardized catch rates peaked at  $24.27 \pm 0.49$  kg/net panel/day with seven panels and declined to below 15 kg/net panel/day from the eighth panel onwards (Fig. 5b). Similarly, *E. nurse* showed a peak at  $13.87 \pm 0.39$  kg/net panel/day at eight panels, followed by a gradual decline to about 5 kg/net panel/day by the 16th panel (Fig. 5b), indicating diminishing returns beyond the optimal panel range.

3.5. Bycatch species composition across net panel configurations

A total of 13 bycatch species were identified in the artisanal catch across different net panel configurations. The most abundant species included *Lates* spp., *H. forskahlii*, *A. baremose*, and *Tilapia* spp. (Fig. 6). Other species included *Protopterus aethiopicus* (marbled lungfish), *Malapterurus electricus*, *Clarias gariepinus* (North African catfish), and *Caridina nilotica* (a freshwater shrimp of the family Atyidae) (Fig. 6). *Lates* spp. exhibited a marked increase in catch rate with panel number, ranging from approximately 1 kg/boat/day at six panels to ~ 15 kg/boat/day at 15 panels. Other species displayed more variable trends across net panels. For example, *A. baremose* attained peak catch (3 kg/boat/day) at nine panels, while *H. forskahlii* exhibited dual peaks at

seven and 15 panels, each with ~ 5 kg/boat/day (Fig. 6). The “other species” category included *Bagrus bajad*, *Labeobarbus bynni* (Nile barb), *Mormyrus* spp. (elephant-snout fishes), and *Schilbe* spp. (silurid catfishes), all of which were recorded in low quantities (< 0.5 kg/boat/day) (Fig. 6).

3.6. Monthly variation in bycatch rates of four dominant species

Monthly analysis of the catch rates of four bycatch species (*L. niloticus*, *H. forskahlii*, *A. baremose*, and *O. niloticus*) revealed clear seasonal trends (Fig. 7). *Lates niloticus* exhibited elevated catch rates during April to May and November to January. *Hydrocynus forskahlii* showed peaks in January and November, while *A. baremose* peaked in April, June, and between September and November (Fig. 7). These temporal patterns suggest potential links with hydrological cycles or spawning behaviors, relevant for management considerations.

3.7. Size structure of major bycatch species across habitats

The size structure of the most abundant bycatch species in the experimental catch demonstrated distinct habitat-related patterns (Fig. 8). Overall, the light-based fishery captured predominantly immature individuals, when benchmarked against published maturity data (Nakiyende et al., 2013; NELGAP, 2019). Individuals from inshore habitats were generally smaller than those from offshore habitats (Fig. 8). Additionally, offshore habitats yielded fewer individuals of

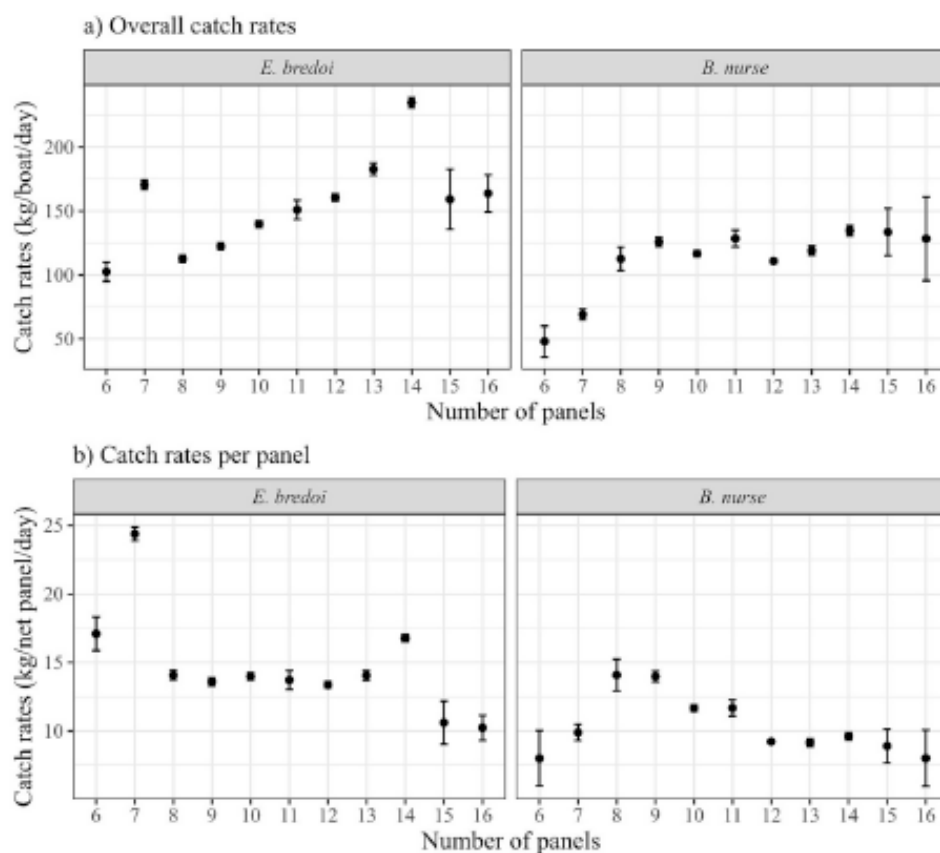


Fig. 5. Mean catch rate ( $\pm$  SE) of *Engraulicypris bredoi* and *Brycinus nurse* across different net panel configurations of small-seine nets utilized in the artisanal fleet on Lake Albert, Uganda.

most bycatch species compared to inshore sites, with the exception of *A. baremose* (Fig. 8). For instance, only 26 individuals (2.1 %) of the 1214 *H. forskahlii* specimens were recorded offshore. Similarly, 48 (9.7 %) individuals of the 493 *L. niloticus* and 43 (19.0 %) specimens of the 226 *O. niloticus* were encountered from the offshore sites. In contrast, 69.8 % (183 individuals out of 262) of *A. baremose* were recorded offshore. Importantly, over 90 % of *O. niloticus* specimens from offshore sites were mature and exceeded the legal minimum harvest size of 20 cm total length, as prescribed by the Fish (Fishing) Rules (Government of Uganda, 2010). This contrasts with the immature size structure observed for most other species, particularly inshore.

#### 4. Discussion

The study presents empirical data that informs the socio-economic and ecological debates surrounding the light-based fishery targeting small pelagic species on Lake Albert. Specifically, it sheds light on the long-standing conflicts between fishing groups, which are primarily driven by perceived high bycatch of juvenile Nile perch and the resulting ban on the SPS fishery, an action that significantly disrupted the livelihoods of communities dependent on its value chains (Africa-Press, 2024; Harvest Money, 2024b; Monitor, 2024; Uganda Times, 2024). The study quantifies catch rates and bycatch composition across different light sources and net panel configurations to offer evidence-based insights. These findings serve as a foundation for further targeted comprehensive stock assessments that are essential for determining the potential risk of the SPS light-based fishery to the large-species stocks, including

*L. niloticus*, and guiding proportionate, scientifically grounded management responses.

By quantifying catch rates and bycatch composition across various fishing methods, the study provides baseline information that can contribute to policy discussion and inform adaptive management considerations within Lake Albert's multi-species fishery. The findings help to bridge knowledge gaps that have fuelled socio-economic tensions, particularly the conflict between fishing groups over perceived juvenile bycatch of large-bodied species, specifically *L. niloticus* and the subsequent ban on the SPS fishery. The analysis of net panel configurations and their relationship to catch rates offers practical insights into fishing efficiency, suggesting areas where regulatory attention could be directed. Moreover, the documentation of bycatch composition, especially the presence of juvenile *L. niloticus*, directly resonates with the core concern underlying current management tensions. Specifically, catch rate data serve as a foundation for identifying trends and guiding further scientific inquiry. Hence, the study highlights the importance of integrating both socio-economic realities and ecological evidence in shaping balanced and inclusive fisheries policy frameworks, especially in data-limited, multi-species ecosystems such as Lake Albert. Therefore, the insights derived from this study can contribute to developing more equitable and sustainable fisheries management considerations for Lake Albert and similar ecosystems, with a focus on conflict resolution and data-informed policy alongside ecological considerations.

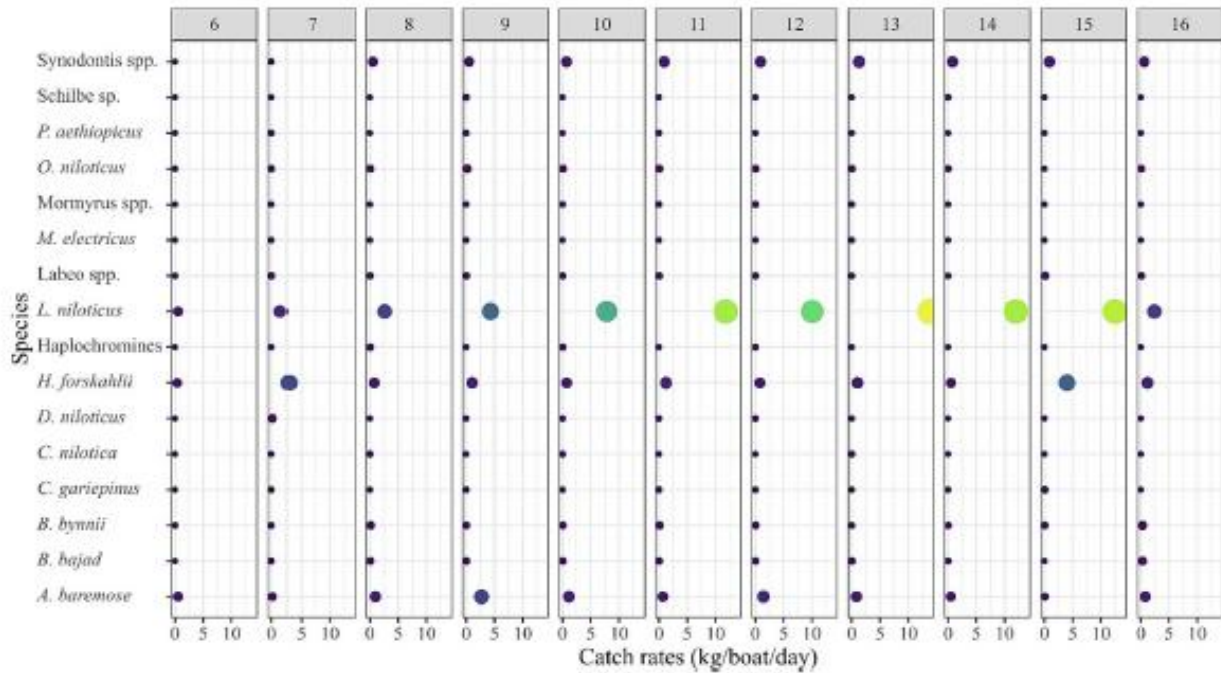


Fig. 6. Mean catch rates of bycatch species across various net panel configurations of small-seine nets used in the artisanal fleets on Uganda’s Lake Albert, Uganda.

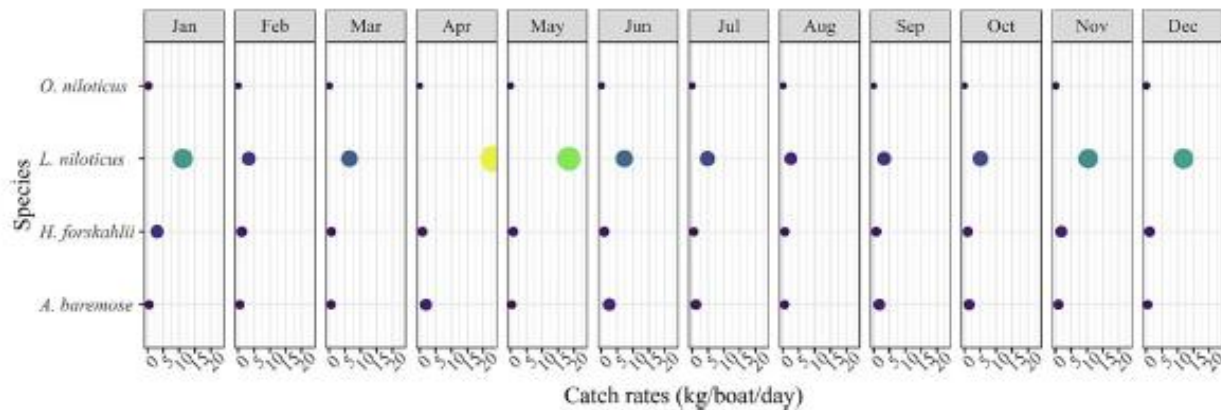


Fig. 7. Monthly variation in daily mean catch rates of four common bycatch species in artisanal catches.

4.1. Catch rates of *Engraulicypris bredoi* and *Brycinus nurse* across light type and net panel configurations

The observed patterns in *E. bredoi* and *B. nurse* catch rates across varying light sources and net panel configurations offer valuable insights into the dynamics of Lake Albert ecosystem. The consistently higher catch rates of *E. bredoi* compared to *B. nurse*, as reported by previous studies (Mbabazi et al., 2012, 2019; Nakiyende et al., 2023), may reflect its greater relative abundance (Trenkel and Rochet, 2003; Ye and Dennis, 2009). However, this trend could also be influenced by species-specific gear selectivity (Thambithurai et al., 2018). For instance, *E. bredoi* may display behavioural traits such as stronger phototaxis (attraction to light) or a greater tendency to school and aggregate within the effective fishing zone of the gear (Blaxter and Parrish, 1965; Pavlov and Kazumyan, 2000), making them more susceptible to capture. Additionally, differences in vertical distribution within the water

column, influenced by diel migration and other behavioural patterns, may influence species-specific catchability in relation to the number and configuration of the net panel (Clark and Levy, 1988).

While relative abundance derived from catch data offer useful insights to a certain degree (Cooke and Beddington, 1984; Hubert and Fabrizio, 2007), interpreting catch rates meaningfully requires a more comprehensive understanding that incorporates species-specific gear selectivity, behavioural ecology, and the stock biomass estimates for the target and incidental bycatch species. Therefore, future research should prioritize comprehensive stock assessments integrating hydroacoustic and trawl survey techniques, to quantify fish biomass and spatial distribution, providing a robust foundation for evaluating fishing pressure and ecosystem dynamics. Complementary studies such as controlled gear selectivity and behavioural assessments of target and non-target species would further enhance the interpretation of catch data and support the development of effective, evidence-based fisheries

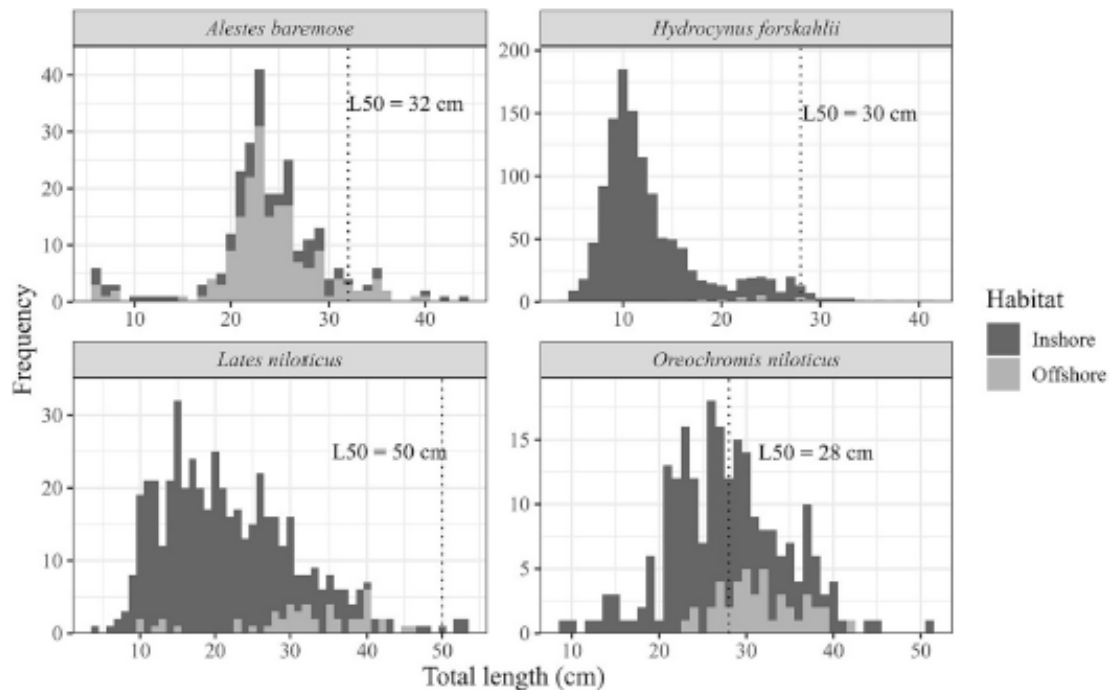


Fig. 8. Length-frequency distribution of dominant bycatch species captured in experimental catches from inshore and offshore habitats of Lake Albert. Dotted vertical lines indicate the size at 50% maturity ( $L_{50}$ ) for each species, based on previous studies (Nakiyende et al., 2013; NELSAP, 2019). For *Lates niloticus* and *Oreochromis niloticus*, the  $L_{50}$  also corresponds to the minimum legal harvest sizes as stipulated in the Fish (Fishing) Rules (Government of Uganda, 2010).

management strategies.

Catch rates of *E. brederi* and *B. nurse* were significantly reduced in the absence of artificial light, reaffirming the central role of light in driving the efficiency of this specific fishery (Nguyen and Winger, 2019). While the practical effectiveness of light is evident in its historical and widespread use by fishers in the East African region (Lvfo, 2020, 2022; NaFIRRI, 2012; Nakiyende et al., 2023; Nguyen and Winger, 2019; Solomon and Ahmed, 2016; Wandera, 1990), empirical quantification remains essential, particularly in the context where policy decisions have been made to restrict and ban its use under the assumption that light is non-essential or ecologically harmful (Harvest Money, 2024a; The Cooperator News, 2024; Uganda Times, 2024). The schooling behaviour and foraging strategy of these SPS make them highly responsive to light stimuli (Blaxter and Parrish, 1965; Pavlov and Kasumyan, 2000). Light-induced aggregation has also been observed to enhance predator foraging efficiency (Becker et al., 2013). These dynamics underscore why light is not merely a supporting tool, but a fundamental ecological and technological driver of catch success in this fishery, necessitating science-based guidance in ongoing policy formulations.

In contrast to previous studies that report reduced catch rates due to increased gear visibility and subsequent fish avoidance in illuminated static gear configurations such as gillnets and trawls (Allman et al., 2021; Senko et al., 2022; Southworth et al., 2020), our study observed significantly higher catch rates during illuminated seine net deployments. This apparent contradiction likely stems from differences in fishing methodologies. Unlike static gears, our study employed a rapid encirclement technique in which the seine net was swiftly deployed around aggregated fish shoals. This technique minimizes the opportunity for fish to escape and effectively counteracts any avoidance behaviour that might be triggered by enhanced gear visibility. The speed and precision of this seine net deployment (commonly referred to as the "Hurry-up" technique), particularly in illuminated zones, facilitates the

swift concentration of fish, ultimately resulting in high catch rates. By contrast, in static gear setup like those examined by Senko et al. (2022), illumination likely increases gear visibility over extended periods, providing fish ample time to detect and avoid the gear. These findings underscore the importance of understanding the interaction between light and gear type and suggest the need for future studies to examine how light influences the behavior of SPS in dynamic gear deployments.

These findings are particularly relevant in the context of ongoing policy debates regarding the sustainability of light-based SPS fisheries in Lake Albert and other African Great Lakes ecosystems. Some stakeholders have advocated for a complete ban on all light use, including solar lights, citing perceived negative impacts on large-species fisheries. These concerns persist despite the absence of viable alternative methods for harvesting SPS stocks. Our findings offer empirical evidence to inform such policy deliberations, highlighting that light is not simply an accessory tool, but an integral component of the SPS fishery's operational framework. Therefore, rather than implementing a blanket ban, a more nuanced, evidence-based policy approach is necessary, one that prioritizes the development of sustainable fishing practices to mitigate potential ecological impacts while recognizing the essential role of artificial light in the SPS fishery.

#### 4.2. Economic and environmental benefits of solar fishing lights

The adoption of solar lighting technologies in Lake Albert and comparable ecosystems such as Lake Victoria has generated considerable conflict. Large-species fishers, especially those involved with the Nile perch fishery have expressed concerns over the use of solar lights, favouring kerosene lanterns, due to perceived detrimental impacts, especially claims of elevated bycatch associated with solar illumination. However, our study found no significant differences in catch rates of SPS and bycatch species across different light sources and intensities tested. This finding challenges the narrative justifying a ban on solar lights and

helps bridge the policy divide by providing empirical data where it has been previously lacking. Evidence-based insights such as these are essential for guiding informed fisheries policies. In particular, they support the continued adoption of solar lights, which offer well-documented economic and environmental advantages (Aitken and Scholle, 2015; Mangeni-Sande et al., 2019; Mulyono et al., 2023). These benefits extend well beyond operational ease. Solar lights eliminate the need for frequent refuelling and re-pressurizing lamps during night-time fishing operations, thereby reducing operational downtime and enhancing fishing efficiency. Moreover, their consistent illumination, even under adverse weather conditions, ensures reliable catch performance and contributes to economic stability for fishers (McHenry et al., 2014; Mgana et al., 2019; Mills et al., 2014).

Furthermore, the promotion of solar fishing lights presents a practical opportunity for strategic spatial management of fishing effort on Lake Albert, particularly in the context of ongoing user conflicts and operational constraints. Traditionally, SPS fishers have avoided deeper offshore habitats due to adverse weather conditions, particularly strong winds and storms, which frequently extinguish kerosene-based fishing lights by flipping them into the water, abruptly ending fishing operations and making such expeditions economically unviable. In contrast, solar lights have demonstrated greater resilience under these conditions; even when overturned by waves, they continue to emit light and attract SPS, making offshore fishing more feasible and reliable. By incentivizing the adoption of solar lights for offshore use, fishing pressure could be gradually shifted away from ecologically sensitive inshore areas, critical breeding and nursery areas that support juvenile recruitment and biodiversity conservation (Nakiyende et al., 2013; NELSAP, 2019; Wandera and Balirwa, 2010). Hence, concentrated fishing pressure in shallow inshore habitats could result in substantial bycatch of juvenile fish and may compromise their ecological integrity. Additionally, Uganda's Fish (Fishing) Rules (Government of Uganda, 2010) prohibit the harvest of Nile perch below 50 cm, a size typically achieved only with 5-inch (12.7-cm) gillnets. However, the small-mesh (< 5 mm) nets employed in the SPS light-based fishery are non-selective and increase the risk of harvesting immature fish before they contribute to reproduction, potentially undermining long-term stock sustainability. Excessive juvenile removal, if not balanced across size classes (Breen et al., 2016), can lead to stock collapse, particularly in systems with multiple species with complex life histories. Furthermore, intense fishing in inshore nursery areas can disturb critical processes such as recruitment, predator-prey dynamics, and habitat use patterns essential for ecosystem functioning. Therefore, spatial management strategies that redirect effort offshore also align with existing legal provisions aimed at protecting inshore breeding grounds and ensuring sustainable harvests. As such, offshore light fishing supported by solar technology offers a feasible approach to deconflict use zones, enhance compliance with size-based harvest restrictions, and inform balanced, locally appropriate spatial policies. This approach not only supports sustainability but also responds directly to operational constraints cited by fishers themselves.

#### 4.3. Optimal net panel configurations for sustainable fishing

The analysis of SPS catch rates across varying net panel configurations offers empirical data to support evidence-based decision making in the context of Lake Albert's multi-species fishery. Fishers are highly adaptive, consistently optimizing gear deployment based on practical experience and economic consideration. This trend is evident on Lake Albert, where the continuous increase of net panels has unfortunately escalated conflicts with those opposed to this practice (NafIRRI, 2012; Nakiyende et al., 2023). Our study identifies a threshold beyond which further increase in net panels result in diminishing returns for SPS catch and increased incidence of non-target species, including juveniles of large-bodied species such as *L. niloticus*. Recognizing this observation is essential for informing discussions on gear regulation, especially in light of stakeholder conflicts over bycatch and resource use equity. Therefore,

this study highlights patterns that can guide policy dialogue, balancing efficient SPS harvests with reduced bycatch risks and ecosystem considerations for the long-term resource sustainability of Lake Albert's multi-species fishery. This could be achieved through development of gear configuration guidelines that maximize catch of target species while minimizing operational inefficiencies and potential ecological disturbances.

#### 4.4. Bycatch composition across light types, light intensities, habitats, and net panel configurations on Lake Albert

The study documented a diverse array of non-targeted species across all light treatments, habitat types, and net configurations, in both experimental and artisanal catches, consistent with similar studies on Lake Victoria (Oula et al., 2022). The use of artificial lights in fishing enhances the target species capture by promoting shoaling behaviour, a phenomenon well-documented in SPS (Becker et al., 2013; Blaxter and Parrish, 1965; Mgana et al., 2019; Pavlov and Kazumyan, 2000; Solomon and Ahmed, 2016). Variation in catch composition between inshore and offshore habitats likely reflects inherent differences in species assemblages and life-history traits characteristic of these zones. The higher proportion of small individuals and species observed in inshore catches align with the generally higher biodiversity and presence of early-life stages (Nakiyende et al., 2013; NELSAP, 2019; Wandera and Balirwa, 2010) as well as threatened species such as *Lates macrophthalmus* (Albert later; IUCN, 2025) in these shallow, productive areas. Such patterns warrant consideration when developing spatial management strategies for Lake Albert, particularly where legal frameworks restrict harvest of immature fish (Government of Uganda, 2010).

These findings, which show lower bycatch rates in offshore compared to inshore waters, are consistent with patterns reported in other systems (Azees et al., 2021). While our study does not directly assess habitat functionality, previous research on Lake Albert (Nakiyende et al., 2013; NELSAP, 2019; Wandera and Balirwa, 2010) has identified inshore areas as ecologically significant zones for biodiversity maintenance, fish reproduction, and juvenile recruitment. In this context, encouraging offshore-directed fishing effort could contribute to reducing fishing pressure on these ecologically important inshore habitats. The disproportionate capture of immature individuals, particularly in inshore habitats, raises management concerns related to recruitment overfishing, especially in systems where legal frameworks such as Uganda's Fish (Fishing) Rules (Government of Uganda, 2010) emphasize protection of juvenile fish to ensure they reach maturity and contribute to population replenishment. While Hixon et al. (2014) highlight the ecological challenges associated with conserving larger, older fish, in multi-species fisheries like Lake Albert, balancing harvest patterns to prevent both growth and recruitment overfishing remains essential. Therefore, this study provides empirical data to inform targeted spatial and gear-based management interventions aimed at aligning fishing practices with national conservation objectives and ecosystem resilience.

This study identified a correlation between net panel configuration and bycatch rates, revealing that certain species including *L. niloticus*, *H. forskahlii*, *A. baremose*, *Tilapia* spp., and *Synodontis* spp. (squeakers, catfish family Mochokidae) exhibited increased catch rate with an increasing number of net panels. This observation could explain the expansion of net panel usage on Lake Albert from previously six panels to about 20 panels documented (Mbabazi et al., 2012; Nakiyende et al., 2022, 2023). A similar trend of net panel joining has also been documented on Lake Victoria (LVPO, 2020). The observed increase in bycatch with net panel stacking is a key factor contributing to persistent conflicts between the SPS actors and large-species fishers, particularly those targeting the *L. niloticus* on Lake Albert and similarly structured ecosystems such as Lakes Victoria and Kyoga (Nile Post, 2024). The landing of undersize *L. niloticus*, while economically beneficial to the SPS fishers in the short term (Oula et al., 2022), intensifies competition

over shared resources and undermines current gear-specific regulations aimed at protecting juvenile stocks (Government of Uganda, 2010). These outcomes highlight a pressing need for input control measures (Purcell and Pomeroy, 2015) such as clear gear configuration guidelines and enforcement strategies to minimize bycatch-related tensions and support coexistence of the different fisheries within a shared resource system. The study revealed that deploying up to eight net panels, reaching a maximum fishing depth of 16 m, optimized catch rates of *E. bredoii* and *B. nurse* while minimizing bycatch, which dropped to below 2 kg/boat/day. Beyond this configuration, standardized catch rates plateaued, but bycatch, particularly of *L. niloticus*, increased significantly. This finding suggests that excessive net panelling increases overlap with water zone (depths) used by *L. niloticus* and other large-bodied species, potentially escalating gear-related conflicts between SPS and Nile perch fishers (Nile Post, 2024). While these bycatches of large-bodied species may hold economic value to the SPS fishers (Oula et al., 2022), their capture by gears primarily optimized for SPS can complicate management due to existing gear selectivity rules and market segmentation. The results point to the importance of establishing panel configuration guidelines that balance operational efficiency with reduced inter-fishery conflict.

The study revealed elevated bycatch biomass and species richness in shallow inshore habitats, consistent with previous studies (Nakiyende et al., 2013; NELGAP, 2019; Wandera and Balirwa, 2010), which also identified these areas as critical for fish spawning, early development, and species turnover. Their ecological value stems from their role in supporting reproductive cycles, sustaining juvenile recruitment, and maintaining species assemblages that contribute to the overall resilience of the lake's fishery system. Due to their sensitivity to anthropogenic stressors and concentrated fishing effort, protecting these inshore habitats is essential to maintain ecosystem function and long-term fish stock productivity. Specifically, immature bycatch of large-bodied species such as *Lates niloticus* were notably higher in inshore areas less than 10 m deep, where species richness and juvenile presence were elevated. In contrast, catch compositions in deeper waters were more selective for target SPS (*B. nurse* and *E. bredoii*), with reduced bycatch rates. These patterns, along with complementary hydroacoustic assessments, which indicate greater SPS abundance in open lake areas, suggest that offshore fishing could reduce ecological stress on nearshore breeding and nursery habitats. While further investigation is necessary to define exact spatial thresholds, our results offer preliminary guidance for management discussions aimed at aligning gear use with depth zones to minimize bycatch and safeguard juvenile stocks. While incidental bycatch of non-target species during SPS light fishing increased particularly with increasing net panel deployment, many of these species hold economic value and are retained by fishers. Notably, observations from experimental deployments indicated that the large-bodied bycatch individuals, especially *Lates niloticus*, exhibited signs of post-capture viability when handled promptly. This suggests that voluntary live release, where feasible and aligned with fisher practices, may offer a complementary strategy for conserving ecologically important species. Further research is needed to quantify survival rates, fisher willingness, and potential trade-offs before considering broader implementation of such measures.

The study revealed temporal variation in catch rates of commonly retained bycatch species such as *Lates* spp., *H. forskahlii*, *A. baremose*, and *Oreochromis* spp. across the months sampled. Peak catch rates of these species were observed between April to June and November to December, periods that correspond with the rainy seasons in the Lake Albert region (NEMA, 2009). While this pattern may reflect seasonal shifts in fish distribution or catchability, it also highlights the need for further research into the life-history dynamics and temporal availability of these species within the SPS fishery. Understanding such patterns could provide useful insights for guiding adaptive management strategies, particularly in balancing seasonal fishing activities with resource sustainability goals. Targeted seasonal closures have achieved various

management goals worldwide, including increasing fish stocks and improving productivity (Bavinck et al., 2008; Hastings et al., 2017). However, the current findings do not provide conclusive evidence for implementing seasonal closures, and any future regulatory considerations should be based on comprehensive, ecosystem-wide assessments.

The study consistently observed a slightly lower proportion of bycatch with kerosene lanterns across artisanal, experimental, and stakeholders' perception data. This marginal difference may explain the continued opposition to solar lighting alternatives among Nile perch fishers in favour of kerosene light sources. However, the use of kerosene lanterns presents notable environmental, health, and safety risks (Kakodia et al., 2025; Mills et al., 2014; Mills, 2016). These include the potential for oil spills that can contaminate aquatic ecosystems and fish catches, the inhalation of harmful fumes such as carbon monoxide, which poses health risks to fishers, and the danger of fire-related accidents. While systematic data on the frequency of such accidents are limited, recurring anecdotal accounts from fishers and lakeside communities underscore these concerns. In light of these risks, transitioning from kerosene to solar lighting is advisable. Solar lights offer a more environmentally sustainable, safer, and potentially more cost-effective option that aligns with broader goals for sustainable fisheries management.

## 5. Conclusion

This study provides empirical insights into optimizing small pelagic fisheries management on Lake Albert, particularly with respect to fishing gear configuration, catch composition, and the use of artificial light. The findings confirm the critical role of light-assisted fishing in enhancing catch efficiency, with significantly lower catch rates observed in non-lighted control treatments. This reaffirms the functional importance of light in the exploitation of small pelagic stocks in Lake Albert. The results also demonstrate that bycatch composition and quantity vary with fishing depth and net panel configuration. Notably, the proportion of bycatch, especially juvenile individuals of non-target large-bodied species such as *L. niloticus*, was observed to increase in shallower inshore waters (< 10 m) and with the use of more than eight net panels. This depth-related pattern in bycatch suggests that optimizing gear configuration, specifically limiting net panels to eight, which corresponded to a maximum fishing depth of approximately 16 m, can help reduce unintended catches while maintaining target species yields. While seasonal variability in bycatch species composition was observed, further research is necessary to determine whether this aligns with species-specific breeding or migratory patterns. Although kerosene lanterns showed slightly lower bycatch in some instances, their continued use poses notable environmental and health risks. Based on their safety, environmental benefits, and growing cost-effectiveness, the promotion of solar lighting technologies is encouraged. In summary, this study offers data-driven guidance for improving fishing practices and minimizing ecological impacts. The key management considerations supported by the study include: gear-based management (limiting net panel configurations to a maximum of eight to reduce bycatch), depth-based fishing optimization (encouraging operations beyond shallow inshore areas where bycatch tends to be higher), and technological transition (promoting environmentally safer lighting technologies, particularly solar-powered options). These targeted interventions aim to improve selectivity in fishing operations, reduce unnecessary catch of non-target species, and support coexistence of multispecies fishery in Lake Albert.

## 6. Recommendations

Based on the descriptive findings of this study on the light-based small pelagic species (SPS) fishery in Lake Albert, the following practical and evidence-informed considerations are proposed:

Review of net panel configurations to optimize catch efficiency: The study observed that catch rates for *B. nurse* and *E. bredei* plateaued beyond the use of eight net panels (approximately 16 m depth), while bycatch rates, particularly of *L. niloticus*, increased with additional panels. This suggests that limiting net panel configurations to eight may help optimize target SPS catch while reducing unintended catches. This insight could inform future discussions on best practices for gear use within this fishery.

Promote environmentally safer SPS lighting technologies: While catch rates did not significantly vary across lighting types, the operational simplicity and reduced environmental and health risks associated with solar lights (compared to kerosene lanterns) suggest potential benefits in promoting their wider adoption. Awareness and capacity-building programs may help address current knowledge gaps and improve fisher acceptance of solar-based technologies.

Conduct further research on SPS harvesting technologies: Given ongoing user conflicts and gear-specific catch differences, further research into cost-effective, selective, and scalable SPS harvesting methods, such as lift nets or other light-assisted alternatives, is warranted. Such research could help diversify fishing options and reduce gear-related conflicts in the multi-species fishery context of Lake Albert.

Establish long-term monitoring framework: To track trends in SPS abundance, gear performance, and catch composition over time, a standardized monitoring framework is recommended. Led by institutions such as the National Fisheries Resources Research Institute (NaFIRRI), this should include periodic assessments and stakeholder feedback mechanisms to inform adaptive management.

Future studies on spatial and temporal catch dynamics: Observed depth- and season-related variations in bycatch composition call for targeted ecological studies to better understand spatial and temporal dynamics of both target and non-target species. This would provide a firmer foundation for assessing habitat use, potential breeding patterns, and whether spatial or seasonal fishing measures might be justified in the future.

#### Data availability

The data for this manuscript has not yet been posted in any repository but will be availed on request.

#### CRediT authorship contribution statement

Herbert Nakiyende: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. Jackson Efitre: Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Conceptualization. Anthony Basoomai: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis. Dismas Mbabazi: Writing – review & editing, Writing – original draft, Validation, Methodology, Conceptualization. Anthony Taabu-Munyaho: Writing – review & editing, Validation, Supervision, Conceptualization. Winnie Nkalubo: Writing – review & editing, Supervision, Conceptualization. Gladys Bwanika: Writing – review & editing, Supervision, Conceptualization. Mulwoza Alexi: Writing – review & editing, Methodology, Investigation, Data curation. Mudondo Phelister: Writing – review & editing, Methodology, Investigation, Data curation. Samuel Bassa: Writing – review & editing, Validation, Data curation. Lauren Chapman: Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization.

#### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

the work reported in this paper.

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#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jglr.2025.102690>.

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**Further reading**

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## CHAPTER EIGHT

### ESTIMATION OF BIOLOGICAL REFERENCE POINTS OF *ENGRAULICYPRIS BREDOI* AND *BRYCINUS NURSE* IN LAKE ALBERT

#### CONTEXT

The final chapter of the research component utilizes surplus production models (Schaefer, Fox, and Catch-MSY) to establish the first quantitative harvest limits for Lake Albert's SPS fisheries. By defining Maximum Sustainable Yield (MSY) and associated biological reference points, the study determines that current exploitation levels for both *E. bredoi* and *B. nurse* remain below their sustainable limits. While this suggests a "harvest potential" for increased catch and revenue, the chapter warns against unregulated expansion. The "under-harvesting" indicated by the models must be managed through the technical and spatial constraints identified in previous chapters. The study concludes that any increase in effort should be concentrated in offshore waters and regulated by the 16-meter depth limit to prevent the fishery from breaching bycatch thresholds for non-target species. This provides a data-driven foundation for a "Blue Transformation" that balances economic growth with ecological stability.

The detailed chapter is presented as a publishable manuscript titled "Harvest potential and sustainability of *Engraulicypris bredoi* and *Brycinus nurse* fisheries in Lake Albert: insights from surplus production models"

#### ABSTRACT

Fishery management reference points such as allowable catch, exploitation rates, and maximum sustainable yield (MSY), are pivotal for informing management strategies aimed at mitigating resource depletion. However, in data-limited fisheries, achieving resource sustainability remains a global challenge. Stock assessment models are commonly applied in marine ecosystems to address data limitations and enhance resource sustainability. This study explores the applicability of such models to the data-deficient freshwater fisheries of Lake Albert, an African Great Lake known for its diverse artisanal fishery.

Virtual Population Analysis (VPA), Schaefer, Fox, and Catch MSY models were employed to establish growth parameters and fishery management reference points for two small-sized pelagic fish

species, *Engraulicypris bredoi* and *Brycinus nurse* in Lake Albert. Using length data collected from February 2021 to June 2022 for VPA and catch and effort data from various years (2007, 2012, 2013, 2014, 2019, 2020, 2021, and 2022) for the other models, the study revealed comparable estimates among models, indicating their suitability for informing fisheries management options in the lake.

The estimated MSY ranged from 34,469 to 37,599 tonnes (t) for *B. nurse* and 83,587 and 90,858 t for *E. bredoi*. The MSY estimates exceed the current harvest levels for both species, suggesting under-utilization and potential for increased catch and effort. However, concerns regarding the vulnerability of *B. nurse* to fishing mortality before reproductive maturity highlights sustainability challenges. Species-specific licensing, robust regulations, regular monitoring, and comprehensive ecosystem assessments are essential for the long-term sustainability of their stocks.

**Key words.** *Brycinus nurse*, *Engraulicypris bredoi*, data-limited fisheries, maximum sustainable yields, reference points, stock assessment.

## 8.1. INTRODUCTION

The understanding of key growth parameters and biological reference points of exploited fish stocks, including growth, recruitment, mortality, stock biomass, exploitation rate, size at capture, maximum sustainable yield (MSY), allowable fishing effort (effort at MSY), and allowable catch, is key in guiding effective fisheries management strategies to prevent resource over-exploitation (Haddon, 2011; King, 2013). Unfortunately, such vital information is lacking for many exploited stocks globally (Vasconcellos and Cochrane, 2005; Amorim et al., 2019).

Lake Albert, a transboundary multi-species lake, shared between Uganda and the Democratic Republic of Congo (DRC), situated within the East African Rift Valley faces similar challenges of information scarcity on key biological attributes of its exploited stocks (Nakiyende et al., 2022; 2023). While some data exist on fish species diversity (Wandera and Balirwa, 2010) and catch statistics (Mbabazi et al., 2012; Plisnier et al., 2022; Nakiyende et al., 2013; 2023), essential information such as growth parameters and biological reference points for targeted stocks is lacking. This knowledge gap hampers the development of sustainable management strategies, leaving the exploited stocks vulnerable to over-exploitation or under-utilization (Acere and Mwene-Beyanga, 1990; Von Sarnowski, 2004; Vasconcellos and Cochrane, 2005; Purcell and Pomeroy, 2015).

The consequences of ineffective fisheries management on Lake Albert are evident in the collapse of once dominant fish stocks such as *Citharinus citharus* and the decline of several large-bodied species like *Alestes bareomose*, *Hydrocynus forskahlii*, *Lates niloticus*, *Bagrus bajad*, *Distichodus niloticus* and tilapias (Worthington, 1929; Holden, 1963; Cadwalladr and Stoneman, 1966; Orach-Meza et al., 1989; Von Sarnowski, 2004; Mbabazi et al., 2012; Nakiyende et al., 2013). Two important small pelagic species (SPS), *Engraulicypris bredoi* and *Brycinus nurse*, now dominate the artisanal catches on Lake Albert (Mbabazi et al., 2012; 2019; Kolding et al., 2019), but crucial information on their growth parameters and biological reference points is lacking (Nakiyende et al., 2022; 2023). Additionally, these stocks have experienced considerable increase in fishing effort over the past decade, but with little knowledge of its impacts on their stocks (Plisnier et al., 2022).

Fisheries stock assessment models, such as surplus production models can provide valuable insights into growth parameters and biological metrics to inform sustainable management decisions for exploited stocks (Xiao, 2000; Haddon, 2011; King, 2013; Pedersen and Berg, 2017; Maunder et al., 2020). These models offer practical insights, particularly in data-limited environments such as in Lake Albert, because of their minimal data requirements and fewer assumptions compared to complex ecosystem models (Pons et al., 2020; Samy-Kamal and Teixeira, 2023). Lake Albert supports an important SPS fishery that requires science-driven policies to ensure its sustainability and the well-being of dependent communities within the Lake Albert ecosystem.

The overall goal of this study was to determine the growth parameters and generate biological reference points for *Engraulicypris bredoi* and *Brycinus nurse*, to guide data-driven management decisions for their stock sustainability. The study aimed to answer the following question of what are the sustainable biological reference points, including maximum sustainable yield, allowable fishing effort (effort at MSY), and allowable catch, for *Engraulicypris bredoi* and *Brycinus nurse* populations in Lake Albert?

## **8.2. MATERIALS AND METHODS**

### **8.2.1. Data sources and preparation**

This study utilized effort and catch per unit effort (CPUE) metrics for *Engraulicypris bredoi* and *Brycinus nurse*, obtained pre- (historical data, 2007 – 2014) and during (2019 – 2022) the PhD study period, to estimate biological reference points. These metrics included total annual catch

volumes and total number of boats targeting these species, obtained through catch assessment surveys (recording of catch statistics including catch volumes and economic value in artisanal fisheries) and Frame surveys (a census of fishing effort inputs like fishing boats, gears, and fishers) (Table 8.2-1).

**Table 8.2-1.** Number of boats targeting *Engraulicypris bredoi* and *Brycinus nurse* and their associated annual catch volume (tonnes) on Lake Albert, Uganda between 2007 and 2022. (Missing years between the survey periods lack catch and effort records).

Year	Number of Boats	Annual catch (t)		Data source
		<i>Engraulicypris bredoi</i>	<i>Brycinus nurse</i>	
2007	1,619	34,665	116,702	NaFIRRI, 2007
2012	2,303	78,042	50,905	Mbabazi et al, 2012
2013	2,673	101,048	31,832	NaFIRRI, 2014
2014	3,043	34,096	13,795	NaFIRRI, 2014
2019	3,200	121,106	67,332	NaFIRRI, 2019
2020	3,200	154,463	92,181	NaFIRRI, 2021
2021	1,867	84,158	49,589	Current study
2022	1,867	74,060	28,002	Current study

### Determination of biologic reference points (MSY, Catch at MSY, Fishing effort at MSY)

Biological reference points (MSY, Catch at MSY, Fishing effort at MSY) for *E. bredoi* and *B. nurse* were estimated using the Schaefer (Schaefer, 1954), Fox (Fox, 1970), and MSY-Catch models (Martell and Froese, 2013) models, utilizing annual catch volume and fishing effort data for the period 2007 to 2022, with data gaps (Table 1). Specifically, the Schaefer and Fox models were fitted to both catch and effort data, while the Catch MSY model was fitted to only catch data for its estimation routine.

### Schaefer model, Fox model, and Catch MSY model

The Schaefer and Fox models were based on the following equation:

$$B_{t+1} = B_t + r * B_t * \left(1 - \frac{B_t}{k}\right) - catch_t \dots\dots \text{Equation 1}$$

where  $B_t$  is biomass in year t, r is the intrinsic rate of increase, k is the carrying capacity and  $catch_t$  is the catch in year t.

### Maximum Sustainable Yield (MSY)

The MSY was estimated using the surplus production model within the TropFishR package (Mildenberger et al., 2017) calculated as:

$$MSY = r * \frac{k}{4} = \max\left(\frac{dY}{dF}\right) \dots \dots \dots \text{Equation 2}$$

Where Y represents yield and F signifies fishing mortality. The model iteratively adjusted fishing mortality rates to identify the point at which the yield per unit effort reached its peak sustainable level. It is important to note that the MSY estimates using the catch MSY model (Martell and Froese, 2013) were generated using only the catch data and resilience information for the species, employing equation 11.

Biomass at maximum sustainable yield ( $B_{MSY}$ ) was calculated as:

$$B_{MSY} = \frac{k}{2} \dots \dots \dots \text{Equation 3}$$

**Fishing Mortality at Maximum Sustainable Yield (FMSY)**

Fishing mortality at maximum sustainable yield ( $F_{MSY}$ ), a crucial indicator of fishing pressure, corresponding to the point where the model predicts the highest sustainable yield was estimated as:

$$F_{MSY} = \frac{r}{2} \dots \dots \dots \text{Equation 4.}$$

Exploitation rate at maximum sustainable yield ( $U_{MSY}$ ) was calculated as:

$$U_{msy} = \left(\frac{F_{msy}}{F_{msy} + M}\right) * (1 - \exp(-F_{msy} - M)) \dots \dots \dots \text{Equation 5}$$

The natural mortality (M) values used in Equation 5 for calculating exploitation rate at maximum sustainable yield (UMSY) were derived using empirical life-history based estimators. Specifically, M was estimated using Pauly’s (1980) equation, which integrates key species-specific parameters: von Bertalanffy growth coefficient (K), asymptotic length ( $L_{\infty}$ ), and the annual mean water temperature (T) of Lake Albert. This approach provides a robust approximation of natural mortality for small pelagic species such as *Engraulicypris bredoi* and *Brycinus nurse*, particularly where direct mortality observations are unavailable. The resulting M values were then incorporated into the UMSY calculations to assess sustainable exploitation levels.

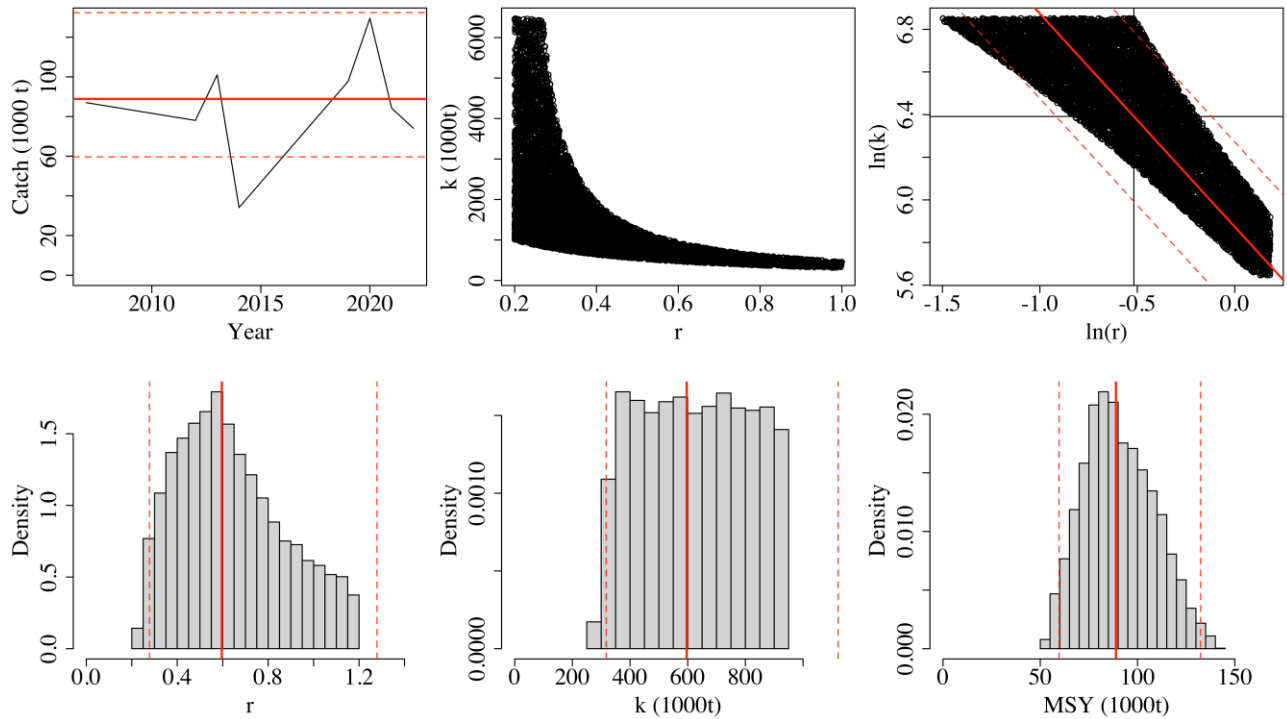
### 8.3. RESULTS

#### Estimated Maximum Sustainable Yield (MSY) and Fishing Effort at MSY ( $F_{MSY}$ )

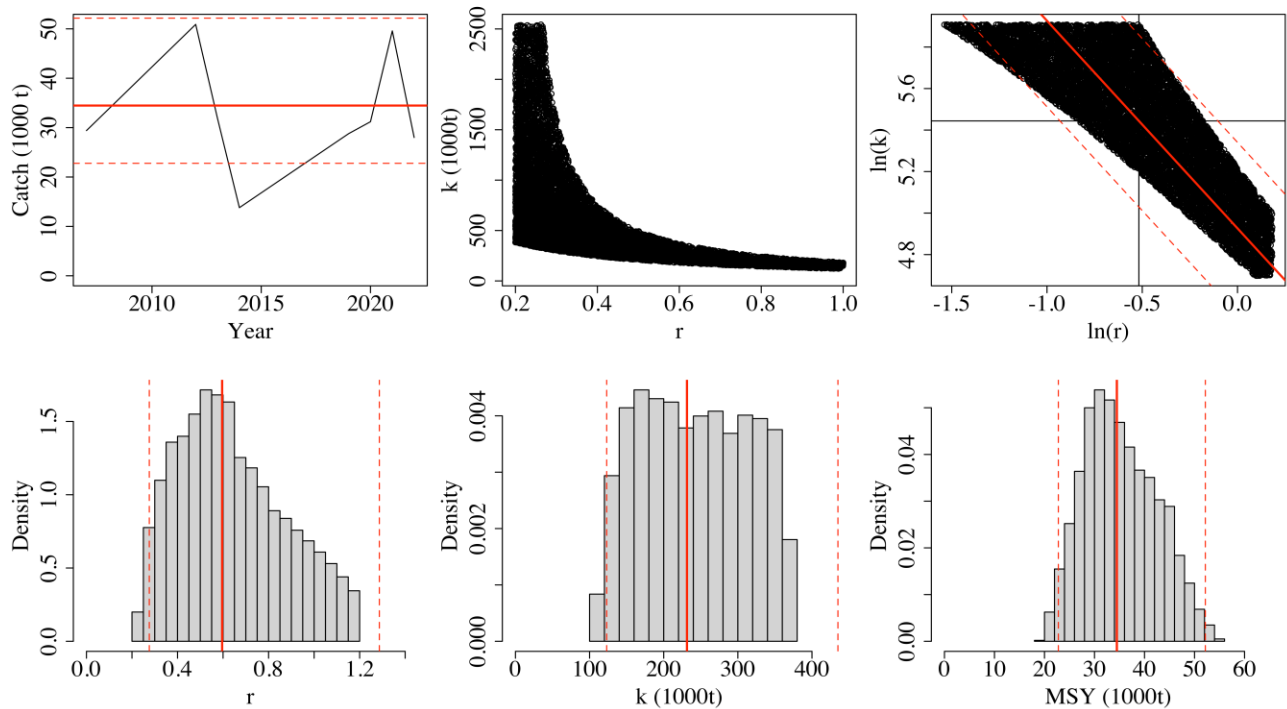
Biological reference points derived from three surplus production models, Catch-MSY, Schaefer, and Fox, revealed key insights into the potential productivity and sustainable harvest levels of *Engraulicypris bredoii* and *Brycinus nurse* in Lake Albert (**Table 8.3-1**).

#### Catch-MSY model estimates

The Catch-MSY model provided estimates for MSY, intrinsic growth rate ( $r$ ) and carrying capacity ( $k$ ), but did not yield estimates for  $F_{MSY}$  (**Figure 8.3-1; Figure 8.3-2; Table 8.3-1**). The MSY predicted for *E. bredoii* in Lake Albert was 88,877 tonnes (t), with a 95% confidence interval of 59,670 to 132,381 t (**Figure 8.3-1**). In comparison, the MSY for *B. nurse* was estimated at 34,469 t, with a 95% confidence interval of 22,776 to 52,166 t (**Figure 8.3-2**). Similarly, the model estimated a higher carrying capacity for *E. bredoii* at 596,517, with a range of 317,245 to 1,121,632 t (**Figure 8.3-1**), compared with *B. nurse*, which had an estimated carrying capacity of 231,366 t, with a range of 123,053 to 435,017 t (**Figure 8.3-2**). The intrinsic growth rates ( $r$ ) for both species were estimated to be within the same range, approximately 0.60, with a range of 0.28 to 1.29 (**Figure 8.3-1 and Figure 8.3-2**).



**Figure 8.3-1.** Graphic output from the Catch-MSY method for *Engraulicypris bredoi* in Lake Albert, based on time series of annual catches from 2007 to 2022. The first panel on the first-row shows the time series of catches with overlaid estimate of MSY (bold red line) and the limits (dotted red lines) that contain about 95% of the estimates. The second panel shows the prior uniform distribution of  $r$  and  $k$ ; which is non-linear with the black region representing the  $r$ - $k$  combinations that are compatible with the time series of catches. The third panel shows a magnification of the viable  $r$ - $k$  pairs in log space, with the geometric mean MSY estimate (bold red line)  $\pm 2$  standard deviations (dotted red lines) overlaid. Panels on the second row show the posterior densities of  $r$ ,  $k$ , and MSY, respectively. In the third panel, geometric mean MSY (bold red line)  $\pm 2$  standard deviations (dotted red lines) are indicated. Data sources include the Catch Assessment Survey Report (NaFIRRI, 2021) for catch estimates from 2007 to 2020 and the current study for catch estimates from 2021 to 2022.



**Figure 8.3-2.** Graphic output from the Catch-MSY method for *Brycinus nurse* in Lake Albert, based on time series of annual catches from 2007 to 2022. The first panel on the first-row shows the time series of catches with overlaid estimate of MSY (bold red line) and the limits (dotted red lines) that contain about 95% of the estimates. The second panel shows the prior uniform distribution of  $r$  and  $k$ ; which is non-linear with the black area representing the  $r$ - $k$  combinations that are compatible with the time series of catches. The third panel shows a magnification of the viable  $r$ - $k$  pairs in log space, with the geometric mean MSY estimate (bold red line)  $\pm 2$  standard deviations (dotted red lines) overlaid. Panels on the second row show the posterior densities of  $r$ ,  $k$ , and MSY, respectively. In the third panel, geometric mean MSY (bold red line)  $\pm 2$  standard deviations (dotted red lines) are indicated. Data sources include the Catch Assessment Survey technical report (NaFIRRI, 2021) for catch estimates from 2007 to 2020 and the current study for catch estimates from 2021 to 2022.

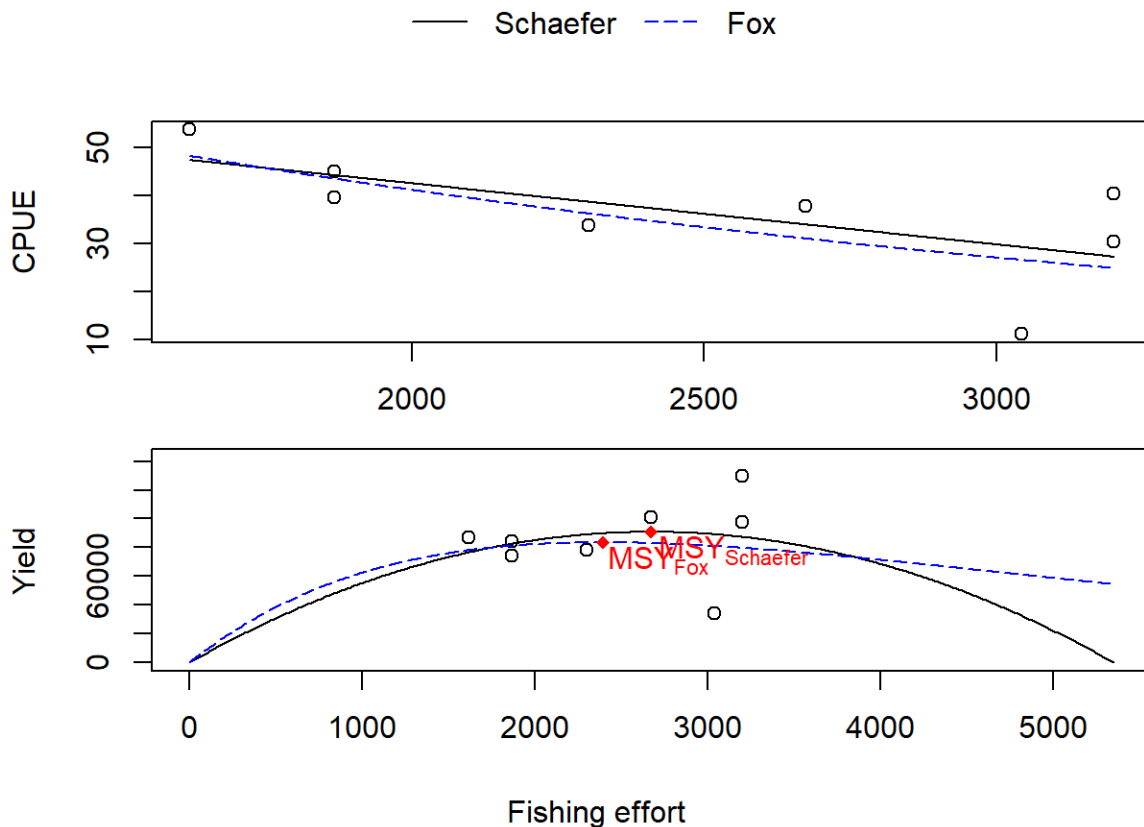
### Schaefer and Fox model estimates

Both the Schaefer and Fox models provided estimates of MSY,  $F_{MSY}$ , and Virgin Biomass ( $B_v$ ), but did not predict intrinsic growth rate and carrying capacity (**Figure 8.3-3** and **Figure 8.3-4**). The Schaefer model demonstrated a better fit and predicted higher estimates of MSY,  $F_{MSY}$ , and  $B_v$  compared to the Fox model for both species (**Figure 8.3-3** and **Figure 8.3-4**). The Schaefer model's

adjusted R-squared values were 0.92 for *E. bredoi* and 0.86 for *B. nurse*, whereas the Fox model showed values of 0.90 and 0.84, respectively. Both models predicted higher values for MSY,  $F_{MSY}$ , and  $B_v$  for *E. bredoi* than for *B. nurse* (Table 8.3-1).

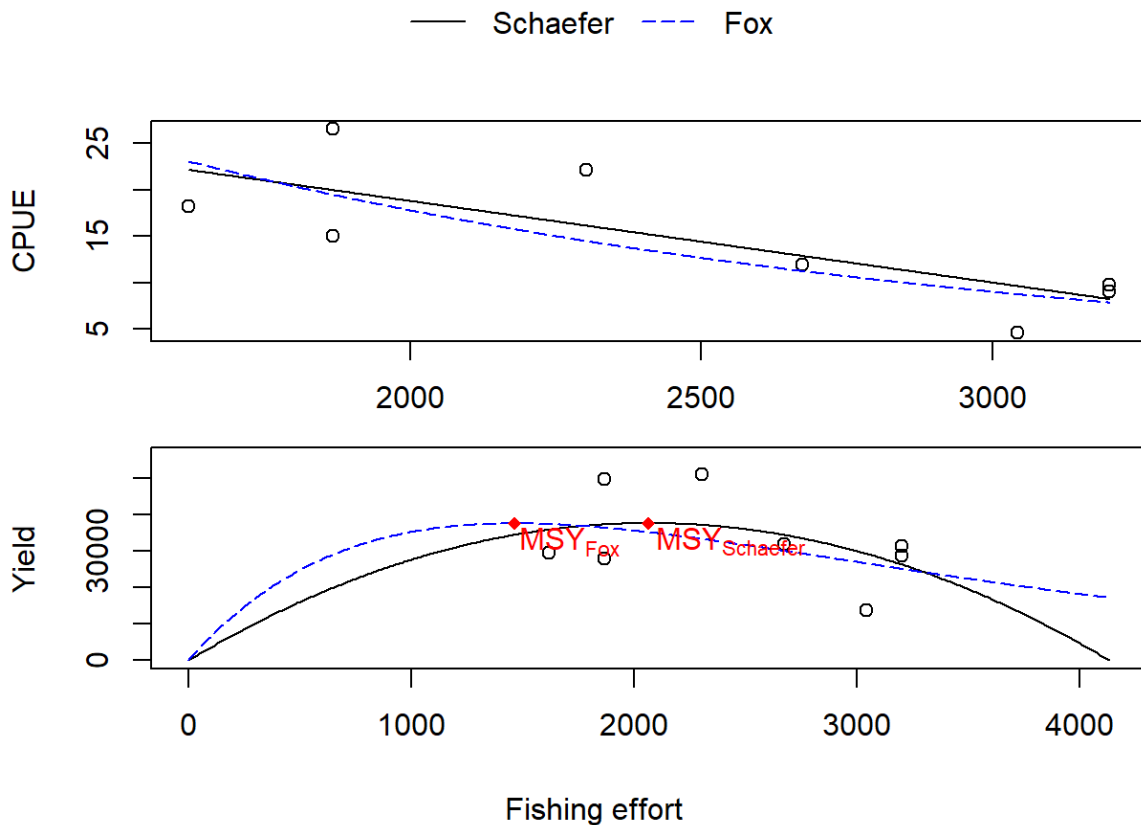
For *E. bredoi*, the Schaefer model estimated an MSY of 90,858 t and an  $F_{MSY}$  2,675 boats  $yr^{-1}$  ( $yr^{-1}$ ), compared to the Fox model's estimates of an MSY of 83,587 t and an  $F_{MSY}$  of 2,394 boats  $yr^{-1}$  (Figure 8.3-3, Table 8.3-1). The Virgin Biomass ( $B_v$ ) for *E. bredoi* was estimated at 67.92 t with the Schaefer model and at 42.55 t with the Fox model (Table 8.3-1).

For *B. nurse*, the Schaefer model predicted an MSY of 37,599 t and an  $F_{MSY}$  of 2,066 boats  $yr^{-1}$ , while the Fox model estimated an MSY of 37,518 t and an  $F_{MSY}$  of 1,464 (Figure 8.3-4, Table 8.3-1). The Schaefer model's virgin biomass for *B. nurse* was 36.40 t, compared to the Fox model's prediction of 4.24 t (Table 8.3-1).



**Figure 8.3-3.** Graphic output of MSY estimates for *Engraulicypris bredoi* in Lake Albert, derived from the Fox and Schaefer Models, using time series of catches and effort data from 2007 to 2022. The upper panel illustrates the relationship between fishing effort (measured in number of active

boats) on the x-axis and Catch Per Unit Effort (CPUE) (measured in kg per boat per night) on the y-axis. The lower panel displays the equilibrium yield curve, with fishing effort (number of boats) on the x-axis and total annual yield (measured in metric tonnes, t) on the y-axis. The red markers indicate the Maximum Sustainable Yield (MSY) and corresponding optimal effort levels (fMSY) as estimated by the Schaefer (solid black line) and Fox (dashed blue line) models.



**Figure 8.3-4.** Graphic output of MSY estimates for *Brycinus nurse* in Lake Albert, derived from the Fox and Schaefer Models, using time series of catches and effort data from 2007 to 2022. The upper panel illustrates the relationship between fishing effort (measured in number of active boats) on the x-axis and Catch Per Unit Effort (CPUE) (measured in kg per boat per night) on the y-axis. The lower panel displays the equilibrium yield curve, with fishing effort (number of boats) on the x-axis and total annual yield (measured in metric tonnes, t) on the y-axis. The red markers indicate the Maximum Sustainable Yield (MSY) and corresponding optimal effort levels (fMSY) as estimated by the Schaefer (solid black line) and Fox (dashed blue line) models.

**Table 8.3-1.** Maximum sustainable yield (MSY), fishing effort yielding MSY ( $F_{MSY}$ ), intrinsic growth rate ( $r$ ), carrying capacity ( $k$ ) and virgin biomass ( $B_v$ ) for *Engraulicypris bredoii* and *Brycinus nurse* in Lake Albert derived from the Catch MSY, Schaefer, and Fox models. Data sources include the Catch Assessment Survey Report (NaFIRRI, 2021) for catch estimates from 2007 to 2020 and the current study for catch estimates from 2021 to 2022. The brackets represent a 95% confidence interval of the parameter estimates.

Species	<i>E. bredoii</i>			<i>B. nurse</i>			
	Model	Catch-MSY model	Schaefer model	Fox model	Catch-MSY model	Schaefer model	Fox model
MSY (t)		88,877 [59,670 - 132,381]	90,858	83,587	34,469 [22,776 - 52,166]	37,599	37,518
$F_{MSY}$			2,675	2,394		2,066	1,464
$B_v$ (t)			67.92	42.55		36.4	4.24
$r$ (year <sup>-1</sup> )		0.60 [0.28 – 1.28]			0.60 [0.28 - 1.29]		
K (t)		596,517 [317,245 - 1,121,632]			231,366 [123,053 - 435,017]		

## 8.4. DISCUSSION

Fisheries reference points are indispensable, especially for assessment of data-limited stocks (Carruthers et al., 2014, Cousido-Rocha et al., 2022). They serve as vital benchmarks for guiding sustainable management practices to prevent overfishing and facilitate rebuilding of stocks (Mace, 2001; Haltuch et al., 2008; 2009; Tong et al., 2010; Mangel et al., 2013; Moffitt et al., 2016). Despite their widespread utilization in fisheries management globally (Dowling et al, 2019, Sharma et al., 2021) and regionally especially for Lake Victoria (Nakiyende and Magnusson, 2015, NaFIRRI, 2018; Nyamweya et al., 2016; Natugonza et al., 2020), their application to Lake Albert has been limited. This study represents a significant advancement, presenting initial model outcomes regarding the population dynamics of *B. nurse* and *E. bredoii* stocks aimed at informing their sustainable management in Lake Albert.

### Potential Yield and Stock Productivity

The biological reference points derived from the surplus production models underscore the high productivity and resilience of both *Engraulicypris bredoii* and *Brycinus nurse*, offering key implications for their sustainable management in Lake Albert. The relatively high MSY values,

ranging between 83,587 and 90,858 t for *E. bredoi*, and 34,469 to 37,599 t for *B. nurse*, indicate substantial harvestable biomass, especially for *E. bredoi*. This demonstrates *E. bredoi*'s potential to support more fishing effort and catch under sustainable management practices (Squires et al., 2017). The higher MSY and carrying capacity for *E. bredoi* can be attributed to the species' biological traits, such as higher fecundity and rapid growth rates compared to *B. nurse* (Froese et al., 2016; 2017), which are conducive to supporting larger populations under optimal conditions. These traits enable *E. bredoi* to replenish its population more quickly, supporting a higher sustainable yield. The intrinsic growth rate ( $r = 0.60 \text{ year}^{-1}$  for both species) is typical of short-lived, fast-growing small pelagic fishes (Musick, 1999; Froese et al., 2008), which are capable of rapid recovery under appropriate management regimes. The high  $K$  values further reflect the large population sizes that can be supported in the lake's ecosystem, particularly for *E. bredoi*, which dominates the pelagic zone.

### **Fishing Mortality and Biomass Considerations**

The estimated  $F_{MSY}$  values of 1,464–2,675  $\text{year}^{-1}$  suggest that both species can withstand moderate to high levels of fishing pressure. However, the wide range of  $F_{MSY}$  and low  $B_v$  values, especially the 4.24 t projected for *B. nurse* under the Fox model, warrant caution. Low biomass at MSY could reflect past or ongoing depletion, pointing to a potential risk of growth overfishing if current exploitation exceeds sustainable limits (Pauly et al., 2002). The differences in MSY and virgin biomass estimates between the Schaefer and Fox models underscore the importance of model selection in fisheries assessments. The Schaefer model, which assumes a linear relationship between biomass and growth (Schaefer, 1954; 1991), often predicts higher yields compared to the Fox model (Fox, 1970), which assumes a logarithmic relationship. This sensitivity to model assumptions highlights the need for robust data and potentially the use of multiple models to cross-verify results.

The Catch-MSY model provided valuable estimates of carrying capacity and intrinsic growth rates, which are crucial for understanding the long-term sustainability of the fish stocks. The relatively similar intrinsic growth rates for both species ( $\sim 0.60$ ) suggest comparable potential for population recovery, but the higher carrying capacity for *E. bredoi* indicates a greater overall resilience (Froese et al., 2016; 2017).

The estimates for MSY and  $F_{MSY}$  were comparable between the Schaefer, Fox, and Catch-MSY models, suggesting high level of reliability of the model outputs to inform management

decisions for *E. bredoi* and *B. nurse* in Lake Albert. Particularly, the estimates for MSY and  $F_{MSY}$  derived from the Schaefer and Fox models exceed the current catch (Table 1) and effort levels (NaFIRRI, 2021b; Nakiyende et al., 2023b). This could indicate potential to increase effort and catch of *E. bredoi* and *B. nurse*. Moreover, both species exhibit a high resilience (Froese et al., 2017) and a moderate vulnerability to fishing pressure (Cheung, 2005), demonstrating their capacity to withstand moderate pressure and potentially double their biomass within a year.

### **Model Uncertainty and Adaptive Management**

The variation in MSY,  $B_V$ , and  $F_{MSY}$  across models highlights the inherent uncertainty in surplus production models, especially in data-limited contexts. For instance, the Fox model tends to produce more conservative estimates compared to the Schaefer model, which may overestimate biomass in some cases (Hilborn & Walters, 1992; Punt et al., 2020). The discrepancy in model outputs therefore indicates the need for careful consideration of model choice in fisheries management (Maunder and Punt, 2013; Cadrin and Dickey-Collas, 2014; Edgar et al., 2019; Maunder et al., 2023). Model limitations such as data inputs dictate the level of analysis of the complex factors influencing stock dynamics and hence the final model outcomes (Gulland, 1983; Sparre and Venema, 1998; Omori et al., 2016).

Surplus production models often oversimplify the complex biological and ecological processes that can greatly influence stock dynamics (Pedersen and Berg, 2017), assuming a direct relationship between stock size and production while neglecting factors such as species interactions, environmental variability, and habitat conditions (Mohsin et al., 2020; Cousido-Rocha et al., 2022). These limitations highlight the importance of developing more integrative and robust ecosystem models in future studies to address such discrepancies and enhance the reliability of fisheries management. Therefore, adaptive and precautionary management approaches are recommended, integrating multiple models and ecosystem considerations (Garcia and Cochrane, 2005).

## **8.5. CONCLUSION**

This study provides the first model-derived biological reference points, including MSY and  $F_{MSY}$  estimates, for *Engraulicypris bredoi* and *Brycinus nurse* in Lake Albert, offering an important initial basis for management consideration. Results from surplus production models suggest that current exploitation levels may be below estimated reference points; however, these findings should

be interpreted with caution. Surplus production models are known to potentially overestimate MSY, particularly where stocks show signals of decline or where data limitations exist, as is the case for both species. Consequently, the results are best viewed as indicative rather than definitive, highlighting relative productivity and exploitation status rather than prescribing immediate increases in fishing effort. While both species exhibit life-history traits associated with productive stocks, precautionary management is warranted to avoid exceeding biological thresholds, especially for *B. nurse*, which appears more sensitive under certain model assumptions. These findings reinforce the need for adaptive management supported by improved datasets and more integrative assessment approaches in future studies.

## **8.6. RECOMMENDATIONS**

Based on the biological reference points derived from three surplus production models, the following recommendations are proposed to promote ecological sustainability while supporting the socio-economic benefits derived from Lake Albert's fisheries:

1. Regulate fishing effort at  $F_{MSY}$  levels: Maintain fishing effort to levels that achieve maximum sustainable yield maintain (MSY). To achieve these targets, the number of fishing boats targeting small pelagic species should be capped at 2,150. This figure is slightly above the 1,867 boats documented in 2021 but remains significantly below the historical peak of 3,406 recorded in 2016. Regulating effort at this level offers a pragmatic balance between ecological sustainability and economic necessity. However, effort control must be complemented by improved licensing systems, strengthened enforcement mechanisms, and continuous sensitization of fishers through community-based education campaigns. Given the schooling behavior of the target species and their susceptibility to lampara nets, catch and effort data should be closely monitored to assess stock responses and inform timely management adjustments.
2. Conduct comprehensive lake-wide stock assessments. Implement multifaceted stock assessments, including fish age, feeding patterns, biomass, and population structure. Incorporate advanced stock assessment methods, such as trawl surveys, acoustics surveys, molecular tools, and innovative fish aging techniques, to refine model parameters.
3. Enhance data collection and integrative ecosystem modeling: Improve data collection and develop robust ecosystem models that consider multi-species interactions. Enhance data on catch, effort, and environmental variables to increase the accuracy and reliability of stock assessments.

4. Lastly, there is a strong need to institutionalize adaptive management frameworks and participatory governance. This includes regular review of biological reference points and management strategies, co-management planning with Beach Management Units (BMUs), and stronger coordination between Uganda and the Democratic Republic of Congo to manage this shared resource. Transboundary cooperation is particularly critical given the migratory and cross-border distribution of these species.

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## CHAPTER NINE

### GENERAL DISCUSSION, CONCLUSION, AND RECOMMENDATIONS

#### CONTEXT

This final chapter serves as the integrative core of the thesis, synthesizing technical, biological, and socio-economic findings into a cohesive framework for the sustainable governance of Lake Albert's small pelagic species (SPS) fisheries. It contextualizes the shift from a fishery historically dominated by large-bodied species to one currently defined by *Engraulicypris bredoi* and *Brycinus nurse*, which now contribute over 70% of total catch volumes. The chapter moves beyond individual data points to address the systemic challenges of "continuous fishing" effort, gear-related conflicts, and the ecological vulnerability of inshore habitats.

Grounding its conclusions in the Ecosystem Approach to Fisheries Management (EAFM), the chapter provides evidence-based recommendations for policy and local action. It advocates for a transition from "blanket" regulations to precision-based management, specifically recommending the institutionalization of a lunar-synchronized "rest holiday" and the enforcement of permanent inshore exclusion zones. By aligning fishing practices with the natural rhythms of the lake and the biological maturation schedules of the fish, this chapter provides a strategic roadmap for balancing immediate food security needs with the long-term ecological stability of Lake Albert.

Ultimately, this synthesis transforms the thesis from a collection of studies into a timely and practical contribution to Uganda's fisheries policy. It underscores the importance of participatory co-management, where scientific evidence on gear selectivity and spatial distribution is integrated with local ecological knowledge to resolve user conflicts and secure the future of Lake Albert's multispecies artisanal fishery.

#### **9.1. Small pelagic fisheries in Lake Albert: Context, Challenges, and Management Gaps**

##### **9.1.1. Emergence and importance of small pelagic fisheries in Lake Albert**

Small pelagic species (SPS) fisheries constitute a critical but historically under-studied component of Uganda's inland capture fisheries. Across major lake systems, including Lakes Victoria, Kyoga, and Albert, SPS have increasingly dominated fish landings following the decline of formerly important large-bodied species due to sustained fishing pressure, habitat degradation, and weak governance. In Lake Albert, *Brycinus nurse* and *Engraulicypris bredoi* have emerged as the backbone of artisanal fish production, contributing substantially to food security, household livelihoods, and

income generation, while also supplying raw material for animal feed and the aquaculture sector (Mbabazi et al., 2012; Kolding et al., 2019; NELSAP, 2019; NaFIRRI, 2021).

Ecologically, these species occupy mid-trophic positions, characterized by small body size, schooling behaviour, rapid growth, and high turnover rates. Economically, they are well suited to low-capital artisanal fishing systems, making them attractive to a growing number of fishers. Over the past three decades, Lake Albert has therefore undergone a marked transition from a fishery dominated by large-bodied species to one increasingly reliant on SPS, fundamentally reshaping exploitation patterns, value chains, and governance challenges within the lake.

### **9.1.2. Expansion of light-assisted fishing and emerging conflicts**

The rapid expansion of the SPS fishery in Lake Albert has been driven largely by the widespread adoption of artificial light-assisted fishing technologies. These technologies increase catch efficiency by aggregating fish at night and have led to short-term gains in catches and fisher incomes. However, their proliferation has also introduced new management challenges, including intensified nocturnal exploitation, high spatial mobility of fishing effort, limited regulatory oversight, and escalating conflicts among fishing groups due to bycatch challenges (Figure 9-0-1) (NaFIRRI, 2012; Nakiyende et al., 2025).

Conflicts have particularly intensified between SPS fishers and those targeting large-bodied species using conventional gears. This study documented several drivers of these tensions, including perceptions of high juvenile bycatch of large-bodied species, competition for fishing grounds, excessive light intensity leading to gear avoidance by larger fish, and concerns over the number of net panels deployed per vessel. Additional issues such as theft of catches and fishing gear have further exacerbated mistrust among user groups (Chapter Three). These conflicts reflect deeper governance and communication failures rather than purely technical or biological problems.

Beyond harvesting, additional constraints persist along the SPS value chain, including poor post-harvest handling, limited preservation and processing infrastructure, low product value, and weak market integration. These factors reduce economic returns and incentivize increased fishing effort to compensate for low margins, thereby reinforcing unsustainable exploitation patterns (Efitre et al., 2023).

### **9.1.3. Governance, co-management, and institutional gaps**

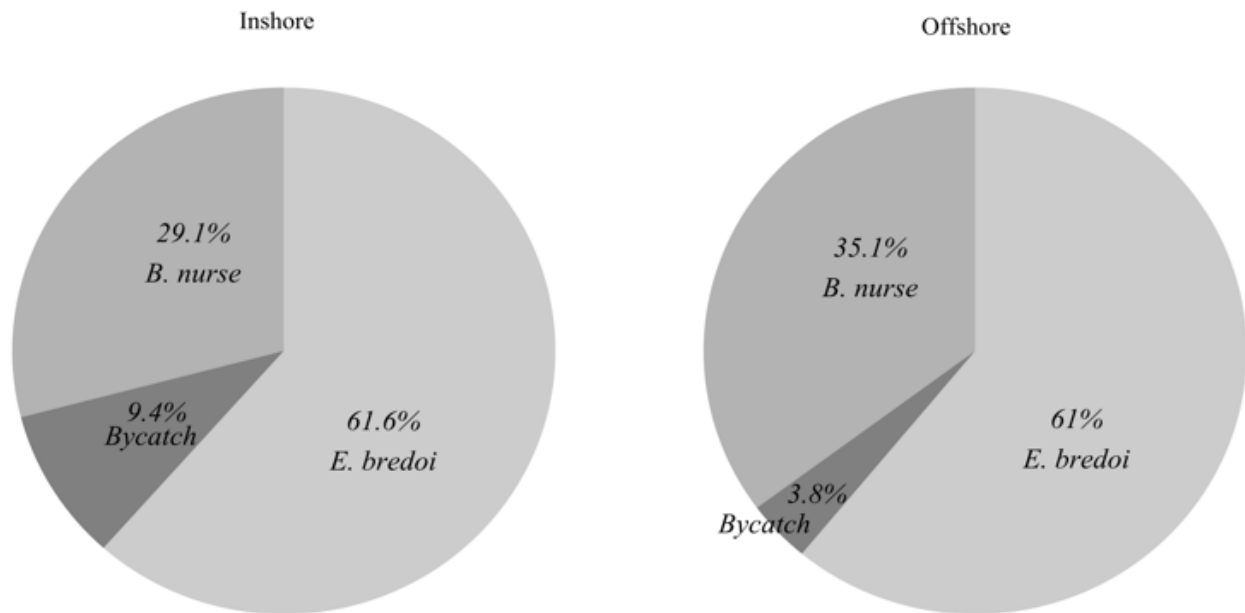
In the absence of strong participatory governance structures, exploitation of the lake's diverse fish stocks has largely followed open-access dynamics, resulting in a perceived excessive fishing effort, weak compliance, and persistent user conflicts. Historically, these governance failures have contributed to overexploitation and drastic declines, and in some cases the disappearance of important commercial large-bodied species such as *Citharinus citharus* (Holden, 1963; Cadwalladr & Stoneman, 1966). Within the SPS fishery, limited regulation, unclear gear standards, and weak spatial controls, especially under light-assisted fishing systems, have heightened the risk of growth and recruitment overfishing. The absence of agreed biological benchmarks and shared management objectives has also fuelled counter-accusations among fishing groups, often unsupported by empirical evidence, thereby undermining collective action and compliance.

While governance failures are central, systemic data limitations continue to constrain effective fisheries management in Lake Albert. Compared to Lake Victoria, the lake remains poorly studied, with fragmented biological, fishery, and socio-economic data, particularly for SPS. This paucity of empirical information limits the formulation of evidence-based management measures, including gear regulations, spatial controls, effort limits, and biological reference points such as maximum sustainable yield (MSY).

### **9.1.4. Ecological complexity and broader development pressures**

Lake Albert is an ecologically sensitive and biodiverse system, supporting approximately 53 fish species with diverse life histories and ecological roles (Wandera & Balirwa, 2010; Nakiyende et al., 2023), more than 20 of which regularly appear in artisanal catches (NaFIRRI, 2021). This multispecies context presents inherent management challenges, particularly in balancing exploitation efficiency, gear selectivity, habitat protection, and bycatch reduction.

The lake is further exposed to multiple anthropogenic pressures, including overfishing, habitat modification, pollution, and persistent conflicts among users. The discovery and development of oil and gas resources within the Albertine Graben add another layer of complexity to the basin's environmental and governance landscape. While this study does not assess the direct or indirect impacts of oil and gas activities on fisheries, these developments are acknowledged as part of the broader context within which fisheries management must operate.



**Figure 9-0-1-1.** Comparison of bycatch between the offshore (deep open) and inshore (shallow) habitats on Lake Albert, Uganda.

## 9.2. Divergent stakeholder perceptions and conflict dynamics in the light-assisted SPS fishery

The expansion of light-assisted fishing targeting small pelagic species (SPS) in Lake Albert has generated sharply divergent perceptions among fisheries stakeholders, reflecting contrasting livelihood interests, gear use patterns, and understandings of sustainability within a multispecies fishery. Fishers targeting *Engraulicypris bredoi* and *Brycinus nurse* generally perceive the SPS fishery as a legitimate, low-capital livelihood that has emerged in response to the historical decline of large-bodied species and limited alternative income opportunities. From this perspective, light-assisted fishing is viewed as an efficient and adaptive technology that enables fishers to exploit abundant schooling species while supporting household food security and local economies. In contrast, fishers targeting large-bodied species—particularly Nile perch—often regard the SPS light fishery as ecologically disruptive and socially unfair, associating it with declining catches, increased gear interference, and erosion of traditional fishing norms.

Key areas of conflict centre on perceptions of excessive fishing effort and the rapid proliferation of solar-powered lights, which are considered by non-SPS fishers to be excessively bright and capable of altering fish behaviour over wide areas. These concerns are closely linked to the practice of net paneling, where multiple net panels are deployed per fishing unit, leading to perceptions

of overcapacity and localized depletion. Bycatch, especially of juvenile large-bodied species in shallow inshore habitats, is another major source of tension, reinforcing beliefs that the SPS fishery undermines recruitment to other commercially important stocks. Spatial overlap between SPS and non-SPS fishing grounds further intensifies conflict, particularly in nearshore breeding and nursery areas where competition for space is highest.

Additional grievances relate to gear and catch theft, which are frequently attributed to nighttime fishing conditions and weak surveillance, and to perceived gear avoidance by large fish in the presence of intense artificial light, which conventional gear fishers associate with reduced catch rates. These ecological and operational concerns are compounded by governance challenges, notably the absence of clear, species-specific management regulations for SPS. Stakeholders repeatedly highlighted uncoordinated and sometimes inconsistent enforcement by the Fisheries Protection Unit (FPU), as well as past or proposed bans on SPS fishing that were widely viewed as unjustified due to the lack of supporting empirical evidence. Such measures have contributed to mistrust between fishers and authorities and reinforced perceptions of inequitable management.

Despite these conflicts, fishing communities also articulated locally grounded conservation norms and management preferences. Traditional practices such as reduced fishing activity or informal rest periods during the full moon, when catchability is perceived to be low, remain influential, with many SPS fishers operating primarily during approximately three weeks of the lunar cycle, coinciding with the new moon, first quarter, and third quarter phases. Stakeholders from both SPS and non-SPS groups expressed support for pragmatic management measures, including limits on fishing effort and net paneling, regulation of light intensity and types, spatial restrictions to protect inshore breeding habitats, designated fishing zones to reduce gear interactions, and periodic rest holidays to allow stock recovery.

Importantly, the study demonstrates that many of these stakeholder perceptions, while sometimes expressed in normative or conflict-laden terms, align with scientific evidence generated in this research. Empirical findings on the concentration of SPS in deep offshore waters, higher bycatch rates in shallow inshore habitats, and the limited influence of light intensity relative to habitat on bycatch provide a basis for reconciling competing viewpoints. Integrating stakeholder knowledge with scientific data offers a pathway toward adaptive, co-managed solutions that balance livelihood needs

with ecological sustainability. By translating shared concerns into evidence-based regulations, such as spatial zoning, gear and effort controls, and clearly defined SPS management frameworks, management institutions can reduce conflict, improve compliance, and promote coexistence among user groups within Lake Albert's multispecies fishery.

### **9.3. Spatial temporal dynamics and light-based effort distribution in Lake Albert**

There is a clear trajectory of increasing fishing effort, with SPS fishing now involving approximately 40% of active boats. This intensified effort is reflected in the overwhelming dominance of SPS, which contributes up to 70% of the total annual catch and nearly 40% of beach-level revenue. This biological dominance is corroborated by acoustic data, where SPS, particularly *E. bredoi* and *B. nurse*, account for the highest proportion of backscatter (~80%) across the lake. This shift from a fishery historically dominated by large-bodied species to one defined by high volumes of small pelagics indicates a profound transition in the lake's ecological structure and economic base.

The findings demonstrate that the lunar cycle is the fundamental driver of both the ecological distribution of Small Pelagic Species (SPS) and the operational intensity of the fishery. The distribution of fishing effort on Lake Albert is inextricably linked to lunar periodicity, which dictates the efficacy of light-attraction technologies. The study reveals a distinct bimodal pattern in effort distribution between the dark (highest effort distribution) and full moon phases (lowest effort distribution), with significant implications for stock sustainability and spatial management. Experimental data confirm that fishing intensity and catch rates peak during the new, first, and third quarters of the lunar cycle, as nightly darkness maximizes the efficiency of light-attraction technologies. These quantitative results provide empirical validation for the perceptions held by local stakeholders regarding the timing of peak productivity. Furthermore, the study identified a significant spatial-temporal correlation, with higher densities of SPS occurring at depths exceeding 15 meters during dark lunar phases.

Despite these natural cycles, a critical management challenge exists: a segment of the fishing community engages in continuous operations throughout the entire month, regardless of lunar illumination. This behavior, documented through effort mapping and stakeholder interviews, bypasses traditional "rest periods" and exacerbates pressure on the lake's multispecies stocks. The lack of a

formalized rest period is particularly concerning for large-bodied bycatch species, which are most vulnerable during these periods of high-intensity, indiscriminate harvesting.

To harmonize these findings into a functional governance strategy, the study recommends the development of a standardized fishing calendar for Lake Albert. By integrating predictive weather and lunar phase data, fisheries managers can institute a mandatory "rest holiday" during the full moon phase. This policy would serve two purposes: it would optimize economic efficiency by focusing effort on periods of high catchability and, crucially, it would provide a periodic biological reprieve for both target and non-target stocks, thereby mitigating the risks of over-exploitation and stock recruitment failure.

#### **9.4. Gear configuration, depth dynamics, and conflict mitigation**

The technical efficiency of the SPS fishery is stringly linked to the vertical reach of the gear, which serves as a primary driver of both productivity and inter-fishery conflict. This study establishes that the number of net panels joined per vessel is the critical determinant of fishing depth and, consequently, catch composition. While optimal catch rates for the target species, *E. bredoi* and *B. nurse*, are achieved at a configuration of eight net panels—corresponding to a fishing depth of 16 meters, exceeding this limit results in diminishing returns for SPS and a significant increase in the bycatch of large-bodied species.

These empirical findings provide a scientific anchor for the "divergent stakeholder perceptions" identified earlier in chapter four. The increased bycatch of juvenile Nile perch (*L. niloticus*) and other high-value species at depths exceeding 16 meters validates the grievances of traditional fishers, who perceive unregulated SPS gear expansion as a direct threat to the recruitment of large-bodied species stocks. This creates a clear socio-ecological link: technical over-extension in the SPS sector drives the "vacuum effect" that fuels spatial competition and undermines social cohesion on Lake Albert.

The 16-meter threshold identified through gear experiments aligns with acoustic backscatter data, which shows that SPS biomass is primarily concentrated in the upper and mid-water columns. Deploying gear deeper than this optimal zone does not significantly enhance SPS yield but instead penetrates the nursery and breeding habitats of non-target species, particularly in inshore regions. Management regulations should therefore limit the number of net panels to eight (~16-meter depth)

to mitigate bycatch related conflicts. By integrating these gear standards with regional spatial zoning and temporal closures in high-bycatch hotspots, management can mitigate user conflicts, ensure ecological stability, and safeguard the long-term sustainability of Lake Albert's multispecies fishery.

### **9.5. Life-history traits and selective pressure of light-assisted fishing**

The biological assessment of *Engraulicypris bredoi* and *Brycinus nurse* reveals a population characterized by high resilience, yet vulnerable to the specific selective pressures of the current light-assisted fishery. Analysis of life-history traits—including size at 50% maturity ( $L_{50}$ ), sex ratios, and positive allometric growth, indicates that both species currently maintain healthy populations with favorable condition factors. These traits align with the ecological profile of short-lived, fast-growing small pelagic species adapted to the variable environment of Lake Albert. However, when synthesized with the findings on gear configuration and spatial effort, these biological indicators suggest a fishery nearing a critical tipping point.

A central concern emerges from the misalignment between gear selectivity and the maturation schedules of the target species, particularly *B. nurse*. While *E. bredoi* appears well-suited to the current exploitation levels, *B. nurse* is highly vulnerable to capture at sizes significantly smaller than its  $L_{50}$ . This size-selective mortality is driven by the incidental capture of juveniles in the fine-mesh nets used for light-attraction fishing, a phenomenon that traditional fishers correctly identify as a threat to stock recruitment. According to life-history theory, sustained removal of immature individuals can drive fishing-induced evolution, forcing shifts toward earlier maturation and reduced somatic growth to compensate for high mortality.

This biological vulnerability ties directly to the "nature and magnitude of conflicts" explored in earlier chapters. The high capture rates of immature *B. nurse* validate the perceptions of the wider fishing community that light-assisted gears act as "vacuums" for juvenile fish. Furthermore, the acoustic backscatter data, which shows SPS dominance, must be interpreted with caution; while biomass is high, the truncation of size structures in *B. nurse* signals a potential trajectory toward life-history change and reduced reproductive potential if current practices persist.

### **9.6. Socio-economic and environmental benefits of solar lights**

The study also explored the socio-economic and environmental benefits of using solar lights in SPS fishing (Chapter 3). Despite the absence of significant differences in catch rates between solar

and kerosene lights, solar lights offer several advantages, including higher turnover of fishing hauls per night, resulting in higher yields. The environmental benefits of solar lights, such as reduced fuel contamination and enhanced safety for fishers and their vessels, make them a preferable option for sustainable SPS harvesting in Lake Albert.

### **9.7. Potential harvest limits and the efficiency-sustainability paradox**

The application of multi-model surplus production frameworks (Schaefer, Fox, and Catch-MSY) provides a robust scientific baseline for the management of *E. bredoi* and *B. nurse*. The convergence of these models suggests that current exploitation levels for both species remain below the Maximum Sustainable Yield (MSY) thresholds, theoretically indicating a "harvest potential" for increased landings and revenue. However, this potential must be interpreted through a "comprehensive lens" that accounts for the technical, biological, and social complexities identified across this dissertation.

While the biomass levels ( $B$ ) are currently above  $BMSY$ , the health of these stocks is inextricably linked to the life-history traits discussed in Chapter six. The "under-harvesting" indicated by the models is primarily applicable to the adult biomass of *E. bredoi*. In contrast, *B. nurse* shows vulnerability due to size-selective mortality of juveniles. Therefore, any expansion of the fishery to reach MSY limits must be managed with precision; if increased effort is achieved through the current unregulated gear configurations (exceeding 16-meter depths), the biological reference points for large-bodied bycatch species will likely be breached long before the SPS MSY is reached.

The surplus production models assume a constant catchability ( $q$ ), but this study (Chapter 5) has demonstrated that  $q$  is highly variable, dictated by lunar phases and regional hotspots. The "potential for increased catch" is therefore not a lake-wide constant but is concentrated during dark lunar phases and at specific depths. If management pursues the expansion of catch without instituting the proposed "lunar fishing calendar," the result will be localized over-exploitation and a "vacuum effect" that drains the system's resilience.

The finding that the SPS fishery is currently "under-harvested" provides a powerful economic incentive for "Blue Transformation," but it also serves as a warning. The "nature and magnitude of conflicts" (Chapter 4) are fueled by the perception that SPS expansion comes at the expense of

traditional fisheries. Increasing catch toward MSY limits without the gear restrictions (16-meter panel depth limit) and spatial zoning recommended in Chapter 7 will exacerbate these user-group tensions.

In conclusion, the surplus production models confirm that Lake Albert's SPS stocks are currently a resilient economic engine. However, the path to "optimal harvest" is not merely a matter of increasing effort. It requires a synthesized management approach that respects biological  $L_{50}$  limits, utilizes standardized gear size and depths to protect bycatch, and adheres to a lunar-based fishing calendar. Only through this integrated framework can the fishery move toward MSY while maintaining the social cohesion and ecological integrity of the Lake Albert ecosystem.

### **9.8. Study limitations**

This study focused primarily on the exploitation dynamics of *Brycinus nurse* and *Engraulicypris bredoi* within the Ugandan waters of Lake Albert, which constrains the direct extrapolation of findings to the entire transboundary lake system. While the spatial design captured key fishing habitats (inshore and offshore) relevant to the SPS fishery, a comprehensive basin-wide assessment incorporating the Congolese waters would be necessary to fully understand lake-wide population connectivity, fishing effort distribution, and ecosystem processes.

In line with the study's fishery-oriented scope, detailed characterization of the physical, chemical, and biological habitat, such as meteorological drivers (precipitation, evaporation, wind regimes, and water residence time), water quality parameters governing primary production, zooplankton productivity, and lake stratification dynamics, was not undertaken. These abiotic and lower-trophic-level processes are critical determinants of secondary production and fish population dynamics, particularly for zooplanktivorous species such as *E. bredoi* and *B. nurse*. Their omission represents an acknowledged limitation and highlights an important avenue for future ecosystem-based research. Nonetheless, habitat influences were indirectly addressed through spatial stratification of fishing grounds and analysis of differences between shallow inshore and deep offshore systems, providing management-relevant insights into habitat sensitivity and bycatch risk.

Additional methodological limitations included logistical constraints that restricted the deployment of artisanal boat seines for ground-truthing acoustic data, limiting species- and size-specific interpretation of hydroacoustic backscatter. Furthermore, catches of *B. nurse* from undersized gillnets ( $\leq 50.8$  mm mesh size) were not comprehensively assessed, constraining a full evaluation of

gear-specific exploitation patterns for this species. Collectively, these limitations position the present study as a foundational benchmark focused on exploitation and governance processes, while underscoring the need for future integrated studies that explicitly link habitat dynamics, lower trophic productivity, and fisheries exploitation to support ecosystem-based management of Lake Albert.

## 9.9. Conclusion

The small pelagic species (SPS) fishery, centered on *Engraulicypris bredoi* and *Brycinus nurse*, has emerged as the ecological and socio-economic cornerstone of Lake Albert. This study provides the first comprehensive, multi-disciplinary assessment of these stocks by integrating experimental fishing, hydroacoustic, spatial effort mapping, and stakeholder perspectives. The findings confirm that SPS now dominate both the lake's biomass and catch volumes, signaling a fundamental regime shift in the ecosystem. While this transition offers a significant "Blue Transformation" opportunity, it also presents complex governance challenges characterized by technical inefficiencies and inter-fishery conflicts.

The research establishes that the sustainability of the SPS fishery is not merely a function of biomass, but of precise technical and spatial regulation. Hydroacoustic and experimental data reveal that while SPS abundance is highest in deep offshore waters (exceeding 20 meters), a significant portion of the current fishing effort remains concentrated in sensitive inshore habitats. This spatial overlap is the primary driver of juvenile bycatch for large-bodied species, rather than the light type or intensity used. Furthermore, the study identifies a "technical optimum" of eight net panels (16-meter depth); exceeding this configuration fails to increase SPS yield while substantially increasing the ecological footprint of the gear.

Socio-economically, the fishery is currently shaped by a "continuous effort" paradox where fishing persists through all lunar phases, despite the natural efficiency gains offered by dark periods. Although surplus production models indicate that *E. bredoi* and *B. nurse* stocks are currently harvested within sustainable biological reference points, the lack of a formalized fishing calendar and standardized gear limits threatens long-term recruitment. The persistent harvest of immature *B. nurse* highlights an urgent need for gear-selectivity adjustments to prevent fishing-induced life-history shifts that could compromise stock resilience.

Lastly, the transition toward a sustainable Lake Albert fishery requires an ecosystem-based management (EBM) framework that moves beyond traditional "blanket" regulations. By implementing science-informed strategies, specifically a 16-meter maximum gear depth, a lunar-based fishing calendar, and offshore-specific zoning, Uganda can mitigate user conflicts and safeguard the multispecies integrity of the lake. This study serves as both a scientific benchmark and a practical foundation for participatory co-management, ensuring that the emergence of small pelagics supports both immediate livelihoods and long-term ecological stability.

## **9.10. Recommendations**

### **9.10.1. Recommendations to management and policy**

Management interventions should prioritize spatial and temporal control to mitigate the "vacuum effect" of light-based gears. Firstly, the Directorate of Fisheries Resources (DiFR) should implement spatially explicit exclusion zones in shallow inshore habitats. Grounded in the Precautionary Principle, these closures protect critical spawning and nursery grounds from the high bycatch rates identified at depths of less than 15 meters.

Secondly, to manage fishing effort effectively, a lunar-synchronized fishing calendar should be institutionalized. By mandating "rest holidays" during the full moon phase, averaging four months of rest per annum, management can reduce total fishing mortality (F) and align harvesting with peak technical efficiency, a strategy supported by both bio-economic theory and stakeholder consensus.

Thirdly, gear standardization must be enforced by limiting SPS vessels to a maximum of eight net panels, ensuring a vertical fishing depth not exceeding 16 meters and the gear mesh size of 8-mm strictly enforced. This regulation is a direct application of selectivity management, specifically designed to minimize the "recruitment overfishing" of large-bodied species like Nile perch.

Fourthly, policy should incentivize the transition to Solar-LED Technology through subsidies or tax exemptions. Anchored in eco-efficiency theory, this shift reduces the operational carbon footprint, eliminates kerosene-related water contamination, and enhances fisher safety. Finally, a review of mesh-size regulations for *B. nurse* is required to align legal gear specifications with the species' length at 50% maturity ( $L_{m50}$ ), thereby safeguarding its reproductive potential.

### **9.10.2. Recommendations to research**

Future research should transition toward transdisciplinary and adaptive management frameworks. There is need for the continuous bio-economic monitoring of SPS stocks. Utilizing the surplus production models established in this study as a baseline, researchers should implement real-time data collection systems, including fishing effort and catch assessment surveys utilizing digital tools such as e-CAS, to detect early signals of fishing-induced life-history shifts. Research must also focus on gear engineering and innovation, specifically the development of cost-effective, deep-water passive gears like modified lift nets. These innovations are essential for the "Blue Transformation," allowing fishers to optimize SPS harvest in offshore waters while maintaining a high degree of species selectivity.

Furthermore, research should address the post-harvest value chain by developing bulk handling and processing innovations. With current post-harvest losses estimated at 30–40%, investing in value-addition technologies is a management necessity to enhance food security and move the SPS fishery up the value chain. Finally, research should focus on Social-Ecological System (SES) Dynamics, investigating how stakeholder engagement and awareness campaigns can be structured to foster "co-management" and reduce the nature and magnitude of user-group conflicts identified in this study.

### **9.10.3. Recommendations to local communities**

Sustainable governance of Lake Albert relies on the principle of participatory co-management. Local fishing communities and Beach Management Units (BMUs) should take a proactive role in the social enforcement of the fishing calendar and exclusion zones. By adopting sustainable harvesting practices, such as adhering to the 8-panel limit and 8-mm mesh size, communities protect the very recruitment cycles that sustain their long-term livelihoods. Communities should transition from being passive resource users to active citizen scientists, working with research institutions like NaFIRRI to provide local ecological knowledge that can be integrated into adaptive management decisions. These community-led efforts are vital for ensuring that the exploitation of small pelagics supports both ecological integrity and the socio-economic resilience of the Lake Albert basin.

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## APPENDICES

### Appendix 1. Survey Questionnaire Used in documentation of stakeholder perceptions of Light Fishing

#### PREAMBLE

Dear Respondent,

The National Fisheries Resources Research Institute (NaFIRRI), a constituent of the National Agricultural Research Organization (NaRO), is mandated to conduct research of national and strategic importance in various fields, including capture fisheries, aquaculture, water environment, socio-economics, information communication and any emerging issues within the fisheries sector. As part of our ongoing efforts to enhance fisheries management on Lake Albert, we wish to undertake a comprehensive study focusing on the use of fishing lights in the harvest of small pelagic fish species (SPS), specifically *Engraulicypris bredoi* (locally known as muziri) and *Brycinus nurse* (ragoogi).

We kindly request your participation in a community survey designed to gather insights into perceptions regarding light fishing practices and the harvest of small pelagic species within Lake Albert. This survey is an integral part of a broader research initiative aimed at understanding the socio-economic dynamics surrounding fisheries management in this region.

Your input is invaluable and will directly contribute to the development of sustainable fisheries management strategies for Lake Albert. The data collected will be utilized solely for research purposes, with the aim of enhancing our understanding of the challenges and opportunities associated with light fishing and the harvest of small pelagic species. This information will be integrated with quantitative assessments to guide the promotion of harmonious co-exist within the multi-species fishery of Lake Albert.

We assure you that all information provided will be treated with utmost confidentiality, and your anonymity will be maintained throughout the research process. Your participation in this survey is entirely voluntary, and you may choose to withdraw at any time without consequence.

Thank you for your cooperation and valuable contribution to this important research endeavor.

For any inquiries regarding the study, feel free to contact the Director of Research, Research Team, National Fisheries Resources Research Institute (NaFIRRI), P.O. Box 343, Jinja. Email: [director@firi.go.ug](mailto:director@firi.go.ug); [director.nafirri@naro.go.ug](mailto:director.nafirri@naro.go.ug); Tel: +256772671216.

## Instructions

Tick appropriate answers for structured questions

Fill provided spaces for open ended questions

### Qualitative Data Survey Questionnaire

Date	Water body	District	Sub-county	Landing site

#### A. BASIC INFORMATION

Status of respondent, tick appropriately (Boat owner/Crew/ Processor /BMU leader/Fisheries staff/)  
Other category (specify) \_\_\_\_\_

Sex of respondent, tick appropriately (Male/Female)

Age group (a) > 20 years (b) 20 – 35 years (c) Above 35 Years

Residence at landing site: (a) Resident (b) Non resident

Respondent contact (if applicable): \_\_\_\_\_

How long have you been on this landing site? \_\_\_\_\_

#### B. EFFORT AND FISHING (LIGHT FISHING BOATS ONLY)

1. Boat Type (1) Congo Barque – CB (2) Sesse Flat at one end - SF (3) Parachute - PA

2. Boat propulsion mode: Sail/Paddle/Engine/Other, If engine (HP) \_\_\_\_\_

3. When did you start using light fishing technologies on Lake Albert? \_\_\_\_\_

4. What species do you target using light fishing technologies (1) *Engraulicypris bredoi* (2) *Brycinus nurse* (3) Others (Specify) \_\_\_\_\_

5. What gears do you use to harvest the species mentioned above? (1) Small seine nets (2) Perforated basins (3) small size  $\leq 2$  inches (4) Others (Specify) \_\_\_\_\_

6. How many gear units do you use per boats? (for Small seines, state the panels): \_\_\_\_\_

7. How many fishing crew (barriers) are employed in each boat? \_\_\_\_\_

8. What type (source) of light do you use: Kerosene lamps/Solar bulbs/Generator bulbs Others (specify) \_\_\_\_\_

9. Number of rafts (rigs) per boat: \_\_\_\_\_
10. Number of bulbs per light raft (rig): \_\_\_\_\_
11. Total number of bulbs/lumps in a boat \_\_\_\_\_
12. How many days do you fish in a month? \_\_\_\_\_
13. How much catch do you land in a day (\_\_\_\_\_ basins; \_\_\_\_\_ kilograms)?
14. How long have you been engaged in the fishing activity? \_\_\_\_\_
15. Prior to light fishing, which fishing gears were you using? (1) Gillnets (2) Long Line Hooks (3) Cast nets (4) Basket Traps (5) Beach/Boat Seines (6) Others (Specify) \_\_\_\_\_
16. What species were you targeting with such gears? (1) Nile perch (2) *Tilapia spp* (3) *Alestes spp* (4) *Hydrocynus spp* (5) *Barbus spp* (6) Others (Specify) \_\_\_\_\_
17. Why did you abandon the original gears in 15 above? (1) Reduced catches in the gears (2) High competition from other fishers (3) Emergence of a new profitable fishery (4) Others  
\_\_\_\_\_
18. What challenges do you face in your fishing activities? (1) Bad weather (2) Inadequate post-harvest handling facilities (3) Low catch value (4) Others (specify)  
\_\_\_\_\_

### C. Perceptions towards light fishing and sources of conflict (ALL CATEGORIES)

- For how long have you lived among the fishing communities on Lake Albert? \_\_\_\_\_
- When did light fishing start on Lake Albert/ Landing site? \_\_\_\_\_
- What type of gears/technologies are used during light fishing? (1) Small seine nets (2) Solar Bulbs (3) Kerosene Lamps (4) Others (Specify) \_\_\_\_\_
- What species do fishers that use light fishing methods target or land? (1) *Engraulicypris bredoi* (2) *Brycinus nurse* (3) Others (Specify) \_\_\_\_\_
- Why do fishers prefer light to harvest the target species? (1) Only method available to harvest the small fish (2) High catches (3) Has no impact on other fisheries (4) Profitable (5) Decline in other species (6) Others (Specify) \_\_\_\_\_
- What kind of fishing grounds do light fishers operate in? (1) Shallow inshore areas (2) Sheltered bays (3) River mouths (4) Deep open waters (5) Every part of the lake
- Are there other species landed as bycatch in these gears/technologies? YES/NO \_\_\_\_\_
- If YES, Name the most common bycatch species (1) *Nile perch* (2) *Alestes spp* (3) *Bagrus spp* (4) *Hydrocynus sp* (5) *Tilapia spp* (6) *Barbus sp* (7). Others (Specify) \_\_\_\_\_

What proportion of the light fisheries catch constitutes bycatch of the large species combined?

<5% (2) 5-10% (3) 10-20% (4) 20-30% (5) 30-50% (6) > 50%

Why are some people not in support of light fishing? (1) High bycatch (2) destruction of fishing ground (3) competition for fishing grounds (4) theft of catch light fishers (5) Unregulated fishing effort (6) Shift from kerosene bulbs to solar bulbs (7) Others \_\_\_\_\_

Is there a resting period (closed season) for light fishing on Lake Albert? YES/NO \_\_\_\_\_

What calendar does the resting period fall? (1) Moon Phase Calendar (2) Year Calendar (3) Both

If Moon Calendar, which specific moon phase? (1) Full moon (2) Half Moon (3) New Moon (Dark Phase)

If Year Calendar, which specific month(s)? \_\_\_\_\_

What is the basis for selection of the resting period indicated above? (1) Low catches (2) Bad weather (3) Agreed by Beach Management Committee (4) Breeding period (5) Random

Would you support the idea of a resting period (closed season) for light fishing? YES/NO \_\_\_\_\_

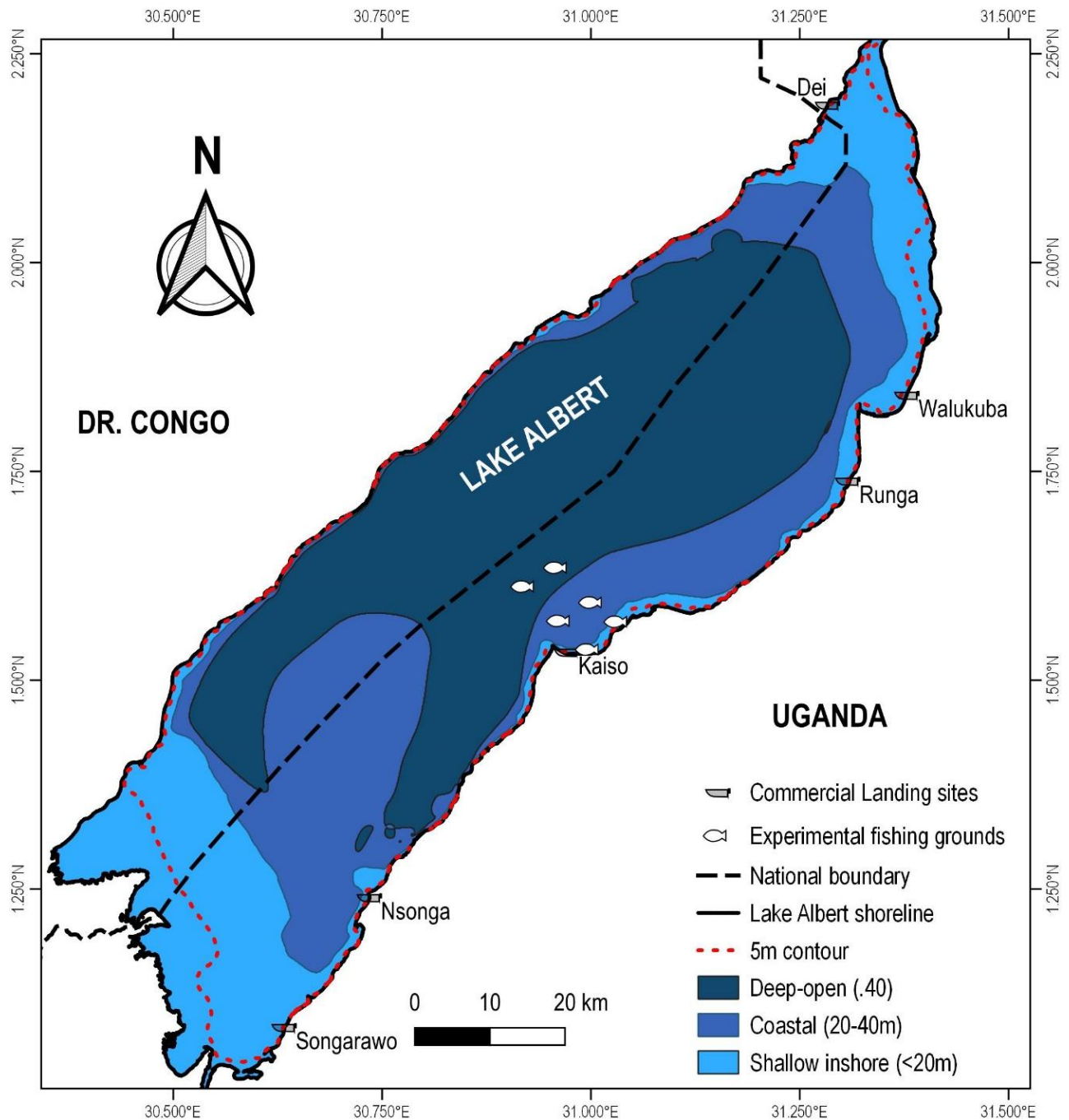
If YES, which Calendar would you suggest? (1) Moon Phase Calendar (2) Year Calendar (3) Both

What benefits do you expect to see if a resting period is instituted? (1) reduced conflicts (2) recovery of stocks of the large sized species (3) Allow fish to breed/ spawn (4) sustained catches (5) Others (Specify) \_\_\_\_\_

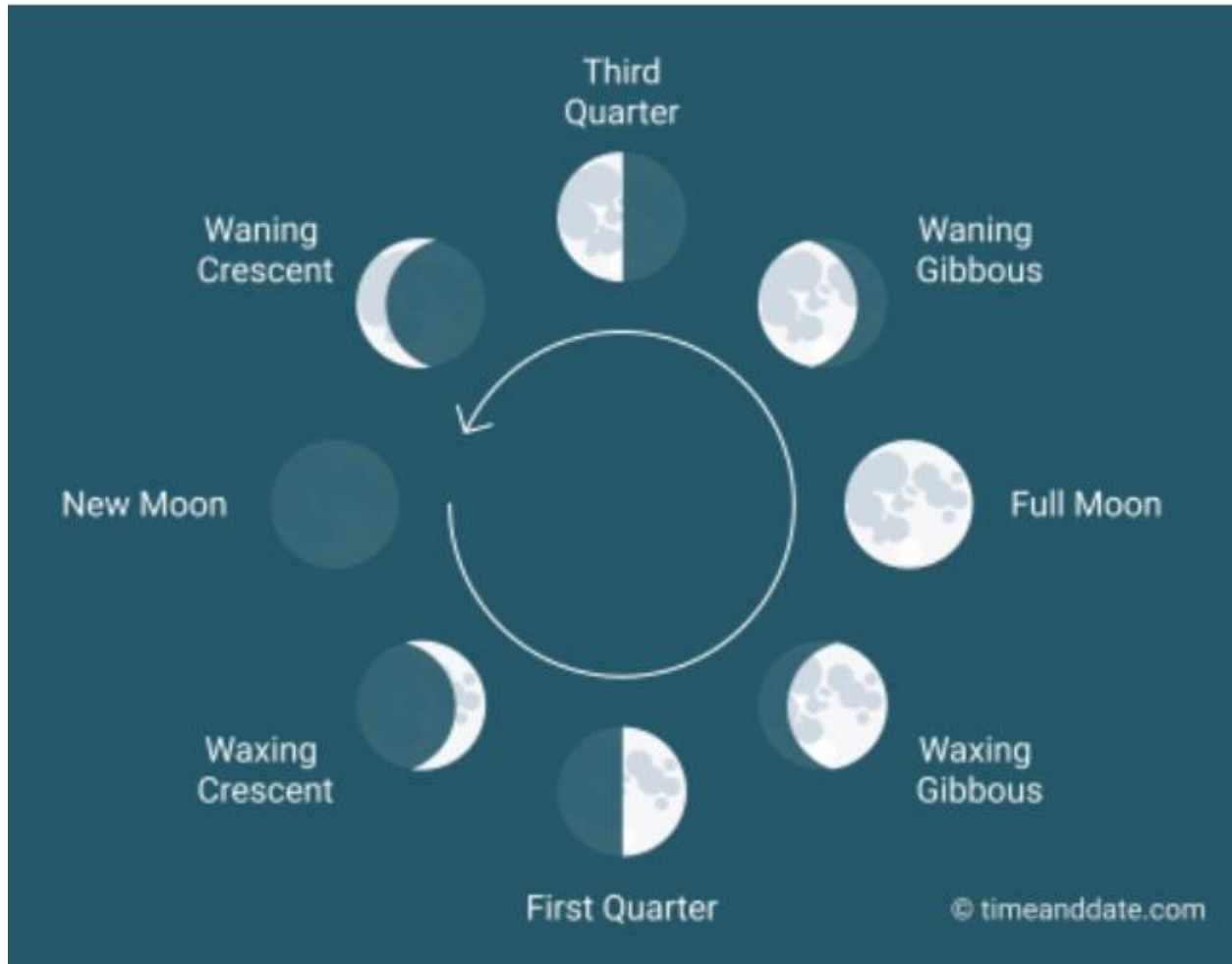
What management measures would suggest for light fishing? (1) fishing effort Control (2) Gear Size Restriction (3) Catch Control (4) Closed Season (5) Closed Area 6) All options (7) Others (Specify) \_\_\_\_\_

Suggest ways for harmonious co-existence of all fisheries in Lake Albert \_\_\_\_\_

**Appendix 2:** Bathymetry Map of Lake Albert showing three major depth Stata Shallow Inshore, Coastal (Mid-Deep), and Deep Open (Offshore).



**Appendix 3.** Moon Phases (Lunar cycle): Sampling was conducted during the four major phases: New moon, First Quarter (Waxing moon), Full moon, and Third quarter (Waning moon).



**Appendix 4.** Sample of a moon calendar employed in data collection in 2020 (<https://kalender-365.de/lunar-calendar.php>).

Lunar Calendar 2020

### Lunar Calendar 2020

● = New moon    ☾ = Waxing moon, half moon    ○ = Full moon    ☾ = Waning moon, half moon  
 ☉ = Lunar eclipse, full moon

January							February							March									
Mo	Tu	We	Th	Fr	Sa	Su	Mo	Tu	We	Th	Fr	Sa	Su	Mo	Tu	We	Th	Fr	Sa	Su			
1			1	2	☾	4	5	5					1	☾	9						1		
2	6	7	8	9	☉	11	12	6	3	4	5	6	7	8	○	10	☾	3	4	5	6	7	8
3	13	14	15	16	☾	18	19	7	10	11	12	13	14	☾	16	11	○	10	11	12	13	14	15
4	20	21	22	23	●	25	26	8	17	18	19	20	21	22	●	12	☾	17	18	19	20	21	22
5	27	28	29	30	31			9	24	25	26	27	28	29		13	23	●	25	26	27	28	29
																14	30	31					
April							May							June									
Mo	Tu	We	Th	Fr	Sa	Su	Mo	Tu	We	Th	Fr	Sa	Su	Mo	Tu	We	Th	Fr	Sa	Su			
14			☾	2	3	4	5	18				1	2	3	23	1	2	3	4	☉	6	7	
15	6	7	○	9	10	11	12	19	4	5	6	○	8	9	10	24	8	9	10	11	12	☾	14
16	13	☾	15	16	17	18	19	20	11	12	13	☾	15	16	17	25	15	16	17	18	19	20	●
17	20	21	22	●	24	25	26	21	18	19	20	21	●	23	24	26	22	23	24	25	26	27	☾
18	27	28	29	☾				22	25	26	27	28	29	☾	31	27	29	30					
July							August							September									
Mo	Tu	We	Th	Fr	Sa	Su	Mo	Tu	We	Th	Fr	Sa	Su	Mo	Tu	We	Th	Fr	Sa	Su			
27			1	2	3	4	☉	31					1	2	36		1	○	3	4	5	6	
28	6	7	8	9	10	11	☾	32	○	4	5	6	7	8	9	37	7	8	9	☾	11	12	13
29	13	14	15	16	17	18	19	33	10	☾	12	13	14	15	16	38	14	15	16	●	18	19	20
30	●	21	22	23	24	25	26	34	17	18	●	20	21	22	23	39	21	22	23	☾	25	26	27
31	☾	28	29	30	31			35	24	☾	26	27	28	29	30	40	28	29	30				
								36	31														
October							November							December									
Mo	Tu	We	Th	Fr	Sa	Su	Mo	Tu	We	Th	Fr	Sa	Su	Mo	Tu	We	Th	Fr	Sa	Su			
40			○	2	3	4	44						1	49		1	2	3	4	5	6		
41	5	6	7	8	9	☾	11	45	2	3	4	5	6	7	☾	50	7	☾	9	10	11	12	13
42	12	13	14	15	●	17	18	46	9	10	11	12	13	14	●	51	●	15	16	17	18	19	20
43	19	20	21	22	☾	24	25	47	16	17	18	19	20	21	☾	52	☾	22	23	24	25	26	27
44	26	27	28	29	30	○		48	23	24	25	26	27	28	29	53	28	29	○	31			
								49	☉														

**Appendix 5.** Field data collection form for experiments on light type and light intensity.

Date ..... Station ..... Experiment (**Light Type/ Light Intensity**) Habitat  
**(Inshore/ Offshore)** Moon Phase: **(N) (Q) (F) (T)** Season **(W)(D)**.

Light Type/Intensity (KPL and SPB-M)	<b>Control (0)</b>		<b>1</b>		<b>2</b>		<b>3</b>		<b>4</b>	
Light Type/Intensity (SPB-S) (lumens)	<b>Control (0)</b>		175		275		300		375	
No. of net panels (net depth in meters)										
Haul No.										
GPS Coordinates (Latitudes)										
GPS Coordinates (Longitudes)										
Depth (meters)										
Temperature (°C)										
Time start (light deployment)										
Time end (net hauling)										
Fishing duration (Minutes)										
Target species total weight (kg)										
<i>Engraulicypris bredoi</i> weight (kg)										
<i>Brycinus nurse</i> weight (kg)										
<b>Bycatch species</b>	<b>No</b>	<b>wt (kg)</b>	<b>No</b>	<b>wt (kg)</b>	<b>No</b>	<b>wt (kg)</b>	<b>No</b>	<b>wt (kg)</b>	<b>No</b>	<b>wt (kg)</b>
<i>Lates spp</i> (Nile perch)										
<i>Oreochromis niloticus</i>										
<i>Tilapia spp</i> (others)										
<i>Hydrocynus forskahlii</i>										
<i>Alestes baremose</i>										
<i>Bagrus bajad</i>										
<i>Labeo-barbus bynnii</i>										
<i>Clarias garipepinus</i>										
<i>Protopterus aethiopicus</i>										
<i>Distichodus niloticus</i>										
<i>Malapterurus electricus</i>										
<i>Mormyrus spp</i>										
<i>Synodontis spp</i>										
Other species (Specify)										

**N**=New moon, **Q**=First Quarter/Waxing moon, **F**=Full moon, **T**=Third Quarter moon/Waning

For other species:

.....  
 ...




Comment: .....

**Appendix 7:** Field data collection form for commercial catch evaluation at study landing sites

Form Number		Sub-county	
Date		Village Name	
Water body		Landing site Name	
Country Name			
District Name		Enumerators' Name	
		Telephone contact	
GPS coordinates	Latitudes:		Longitudes:

Vessel details					Fishing effort details								<i>E. bredoi</i> (muziri) & <i>B. nurse</i> (ragoogi) catch			Large species bycatch details						
Serial Number	Vessel type code	Propulsion code	Number of Crew	Days fished in the last one week	Gear type code	Number of panels	Mesh size for SS (mm)	Mode of gear operation code	Hours fished	Number of Rigs per boat	Number of bulbs per Rig	Type of bulbs	Shape of bulbs	Species Code	No. basins/buckets (Ragoogi/Muziri)	Wt. (kg) 1 basin/bucket	Price 1 basin/bucket Muziri & Ragoogi	Species code	No of fish	Total Wt. (kg)	Price per kg	

Comments: .....





**Appendix 10.** List of publications.

- Nakiyende, H., Chapman, L., Basooma, A., Mbabazi, D., Odong, R., Nduwayesu, E., ... & Efitre, J. (2023). A review of light fishing on Lake Albert, Uganda: Implications for a multi-species artisanal fishery. *Fisheries Research*, 258, 106535.
- Nakiyende, H., Basooma, A., Nyeko, J. I., Okello, W., Rugadya, R., Albrecht, C., ... & Ajode, M. Z. (2023). Limitations for informed decision making and better management of the transboundary Lake Albert fisheries resources. *Journal of Great Lakes Research*, 49(6), 102165.
- Nakiyende, H., Efitre, J., Basooma, A., Bwambale, M., Mbabazi, D., Akumu, J., ... & Chapman, L. (2025). Light-based small pelagic species fishing in Lake Albert: Divergent perceptions, conflicts, and implications for multispecies fishery management. *Journal of Great Lakes Research*, 102664.
- Nakiyende, H., Efitre, J., Basooma, A., Mbabazi, D., Taabu-Munyaho, A., Nkalubo, W., ... & Chapman, L. (2025). Effects of artificial illumination and net panel configurations on small pelagic fisheries and bycatch on Lake Albert, East Africa. *Journal of Great Lakes Research*, 102690.