

**ESTABLISHING A HYDROACOUSTIC SURVEY PROTOCOL FOR MAJOR  
COMMERCIAL FISH SPECIES IN LAKE ALBERT, UGANDA**

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## ABSTRACT

Lake Albert has a total surface area of 5,300 km<sup>2</sup>, shared between Uganda and the Democratic Republic of Congo at 54% and 46% respectively, with an average depth of 25 m and a maximum depth of 58 m. Lake Albert is a multi-species fishery that has supported the livelihoods of riparian communities for many decades by providing food, nutrition, and employment opportunities. The commercial species contributed to the 2020 total annual catch of 348,000 tonnes, valued at US\$175.2 million in Uganda. Lake Albert's fisheries have experienced changes in fish stocks, with a decline in the number and sizes of fish species caught (e.g., Nile perch) and the emergence of small pelagics (Ragoogi and Muziri). Information and data to guide management have remained scanty, limited to fish catches and fishing effort; however, appropriate long-term management would require hydroacoustic studies for ecosystem-based stock management. This study aimed to assess water parameters and their effects on sound speed and acoustic backscatter, characterise fish backscatters, and map the Nautical Area Scattering Coefficient (NASC) alongside fishing areas and landings of the major species. Acoustic sampling was conducted using an EK80 120 kHz transducer, and water parameters were sampled at several hydrostations. The data were processed using the Large-Scale Survey System (LSSS), and the results of the acoustic sampling protocol are discussed.

Fish distribution and acoustic backscatter varied in the three regions of Lake Albert, which could be attributed to the variability in environmental water parameters. There were significant differences in sound speed among the three regions and zones. We distinguished four fish acoustic categories: Nile perch, small pelagics, other demersal species, and other species, with the highest NASC averages of Nile perch and small pelagics in the central region. The main landing sites of *E. bredoi* were concentrated in the central region, with 90% of the catch proportion. *B. nurse* landings dominated the northern region, with 80%, whereas 75% of tilapia were recorded in the southern region. *Lates* spp. are the most important commercial species, and their landings are distributed across all three regions.

Trawl and hydroacoustic surveys with additional echosounder frequencies are recommended to estimate fish biomass, density, and population structure more accurately. Target strength experiments, periodic fish stock assessment studies, and water parameter sampling during stratified and mixed seasons are also recommended for the future.

**Keywords:** Lake Albert fisheries, hydroacoustic surveys, acoustic backscatter, small pelagic species, fish stock assessment, Uganda.

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# 1 INTRODUCTION

## 1.1 Background

Lake Albert (L. Albert) has a total surface area of 5,300 km<sup>2</sup>, of which Uganda and the Democratic Republic of Congo share 54% and 46%, respectively (Cadwalladr and Stoneman, 1966). L. Albert lies between latitudes 0°15' and 1°00' N; longitude 30°21' and 31°25' E, with an average depth of 25 m and a maximum depth of 58 m. L. Albert is situated in the western part of Uganda, more specifically in the Albertine graben part of the western arm of the great rift valley of East Africa. The lake has a catchment area of 41,666 m, drained mainly by the Semliki and Victoria Nile at the southern and northern tips, respectively. Wandera and Balirwa (2010) describe Lake Albert as richly endowed with endemic species diversity. Additional natural resources, including oil wells, natural gas, and wildlife, were documented earlier by Worthington (1929). These resources continue to attract the attention and investment of many international oil companies and environmental conservationists. The L. Albert ecosystem is part of the complex Nile Basin aquatic ecosystem that has contributed to regional economies through fishing, fish proteins for food and nutrition, and employment opportunities for household income (Tamale et al., 2017; Nduwayesu et al., 2023). Other existing natural resources include fresh water for domestic and industrial use, agricultural activities, and wildlife.

L. Albert fisheries consist of a unique fauna with important species that provide fish protein for human and animal nutrition (Clarke et al., 2022). The most important commercial species are Nile perch (*Lates niloticus*), Ragoogi (*Brycinus nurse*), Muziiri (*Engraulicypris bredoi*), Nile catfish (*Bagrus bajad*), Nile tilapia (*Oreochromis niloticus*), Angara (*Alestes baremose*), Ngassia (*Hydrocynus forskahlii*), *Barbus bynni*, and African catfish (*Clarias gariepinus*) (Worthington, 1929; Wandera, 2000). These species contributed to a total annual production of 348,000 tonnes (t) valued at a beach revenue of US\$175.2 million in 2020 from the Ugandan portion of the lake (NaFIRRI, 2021), making it the second most productive lake in Uganda after Lake Victoria (L. Victoria). The highest portion of this total annual fish catch, the two dominant pelagic species Ragoogi and Muziiri, contributed >70% of the annual production reported in 2020.

Oil and gas discovery around L. Albert has attracted international attention and pooled different scientific disciplines to develop mitigation measures to counteract environmental degradation by pipelines and oil infrastructure developments on the lake shorelines. Oil projects predict that oil spillage and environmental alterations will adversely affect biodiversity, wildlife, and lakeside human communities (Wandera and Balirwa, 2010; Steinhauer et al., 2019). However, information on fisheries and ecosystem diversity remains scarce, yet the ongoing developments require holistic scientific information for appropriate aquatic resource management (Stuart Heather-Clark, 2007). Diversity and richness of L. Albert have continuously experienced a decline, with 54 species reported in the 1960s that declined to 33 in the 1990s. The number of commercial species fluctuated between 17 and 14 (Nakiyende et al., 2013).

Available information on fish species abundance is indispensable in stock assessments, which are inferred from catch per unit effort (CPUE), assuming a linear relationship between CPUE and abundance (Maunder et al., 2006). While this assumption is acceptable for providing a rough estimate of fish abundance, especially in data-limited situations, the uncertainty of these estimates in stock assessments is not known (Maunder et al., 2006). Stock assessments estimated using hydroacoustics in Lake Victoria have been successfully implemented annually, and fish abundance, density distribution, biomass, and population structure have been assessed. Some

fisheries of L. Victoria have common characteristics with those of L. Albert and could be benchmarked for L. Albert, for which acoustic data could still be improved.

L. Victoria is the 2<sup>nd</sup> largest freshwater body in the World, with a total surface area of 68,800 km<sup>2</sup> shared by three East African countries; Kenya (6%), Tanzania (51%) and Uganda (43%). It has a maximum depth of 84 m and an average depth of 40 m (Njiru et al., 2010; Njiru et al., 2018). L. Victoria is endemic to diverse fish species, some of which also exist in L. Albert. For example, the major commercial species Nile perch and Nile tilapia exist in both lakes and were introduced to L. Victoria from L. Albert in the 1960s (Greenwood, 1966; Musinguzi et al., 2017). Additionally, both water systems are dominated by small pelagic species (Ragoogi and Muziri in L. Albert and Daaga in L. Victoria). These species share common ecological and biological characteristics and currently contribute to more than 70% of the total annual catch. Unlike in L. Albert, acoustic studies, ecology, and biological information are readily available for L. Victoria species (Inigo et al., 2013; Taabu-Munyaho et al., 2014). The total fish biomass of L. Victoria was 2.82 million tonnes in 2021, and the Nile perch contributed to a biomass of 502,919 t (LVFO, 2021). The availability of acoustic and biological information has been a vital tool for enabling stock assessment in L. Victoria (Getabu et al., 2003; Kayanda et al., 2012).

## 1.2 Fish stock assessments

Fish stock assessments involve different approaches for data acquisition to generate information on fisheries status by applying population dynamics models that guide appropriate recommendations for policymakers, managers, and fisher folk communities (Simmonds and MacLennan, 2005; Conti et al., 2006). Fish stock assessments using hydroacoustic and trawling data, as well as fishery-independent surveys, have been demonstrated to be efficient when estimating fish abundance, spatial distribution, biomass, and population structure in real time (Georgarakos et al., 2011). By applying hydroacoustics, studies and information on spatial and temporal fish densities, biomass, population structure, and fish behaviour can be reported (MacLennan and Simmonds, 1992; Simmonds and MacLennan, 2005; Inigo et al., 2013). Previous fisheries studies conducted in L. Albert have been limited to fishery-dependent information from catch assessment surveys, frame surveys, gill net experiments, fish biology, and water quality studies (Ogutu-Ohwayo and Balirwa 2006; Cowx and Ogutu-Ohwayo, 2019). Therefore, the existing information and data are limited for estimating fish biomass and densities for a proper understanding of the ecological performance of aquatic ecosystems and to establish sustainable fisheries reference points (Richards et al., 1998).

The changes in fisheries of different aquatic systems have been attributed to many factors; however, the key players of changes in fish population dynamics and ecological alterations are fishing practices and management systems (Aloo et al., 2017). Additionally, the effects of climate change, for example, through the rise or fall in water levels and volumes, and environmental degradation, also have an effect. Moreover, the existing illegal, unregistered, and unreported fishing practices around L. Albert have resulted in changes in the availability of major species in the commercial catch. For example, there has been a decline in the size and catch of large species (Ogutu-Ohwayo and Balirwa 2006). The first fishery survey in L. Albert (Greenwood, 1966) reported approximately 42 fish species in the system. These represent the major species targeted as a source of food and for local livelihoods. However, the number of commercial species, catch composition, and abundance have continued to fluctuate over time, and since 1966, the number of species has been declining (Table 1). Fish species such as *Citharinus citharus* and *Eutrophius niloticus* dominated the commercial catch in 1929, although the catches declined and may soon become extinct in the Albertine system (Greenwood, 1966). Studies conducted in different years recorded varying main target species in L. Albert (Table 1). This lake, like other great lakes in

this region, has experienced drastic changes in fisheries and commercial fish stocks, with the dominance of small pelagic species that comprise a large proportion of catch landings (Ogutu-Ohwayo et al., 2020; Nakiyende et al., 2022). The increased demand for fish protein in the Albertine region has led to high fishing pressure, characterised by unsustainable fish practices, leading to the decline of stocks, catches, and disappearance of some species (Cowx and Ogutu-Ohwayo, 2019). Unsustainable fishing practices, poor management systems, and ongoing environmental changes will continue to negatively affect fish stocks and fisheries productivity (Njiru et al., 2014).

Table 1. Trends of the main commercial species reported in L. Albert.

Year	Main species	Total species	Reference
1929	<i>Citharinus spp.</i> , <i>D. niloticus</i> , <i>O. niloticus</i>	42	(Worthington, 1929)
1966	<i>Lates spp.</i> , <i>A. baremose</i>	54	(Wandera, 2000)
1990s	<i>Lates spp.</i> , <i>H. forskahli</i> , <i>Tilapia spp</i>	33	(Ogutu-Ohwayo and Balirwa, 2006)
2010s	<i>Lates spp.</i> , <i>B. nurse</i> , <i>E. bredoi</i>	40	Wandera and Balirwa, 2010
2020	<i>B. nurse</i> , <i>E. bredoi</i>	28	NELSAP-CU, 2019; Nakiyende et al., 2022

### 1.3 Problem statement

L. Albert, as mentioned above, serves as a habitat for ecosystem diversity. The same aquatic ecosystem is surrounded by natural resources such as oil, gas, and wildlife. Previous studies conducted in L. Albert have been limited to fisheries-dependent surveys: fishing effort, catches, fish revenue at the beach level, and fisheries socioeconomics of the riparian communities (Tamale et al., 2017; Nakiyende et al., 2023). However, even with the efforts of these fisheries-dependent studies, data and information on fish size structure, fish densities, and biomass remain scarce. However, such information is vital for developing appropriate fisheries management guidelines. Detailed fisheries studies in L. Albert, which is experiencing species decline and stock changes (Nakiyende et al., 2023), provide data to guide the sustainability and holistic management of fishery resources for people's livelihoods and the national economy. Recent oil discoveries and related oil development activities should be implemented in harmony with other natural resources, such as aquatic resources. The protection of natural resources and environmental conservation are of great importance (Mbabazi et al., 2012). Appropriate fisheries management should ensure holistic ecosystem management amidst existing oil and gas developments in the Albertine region. Developing appropriate and effective fisheries management guidelines will ensure the co-existence and harmony of fisheries resources with other infrastructural developments and a healthy aquatic ecosystem.

### 1.4 Overall objectives

The overall objective of this project is to establish a hydroacoustic survey protocol to guide L. Albert surveys for assessing fish density distributions, biomass, and population structure as biological reference points to guide managers, resource users, and research scientists on fish stock assessment methods of L. Albert.

#### 1.4.1 Specific objectives

The specific objectives of this study are as follows:

- To consider water parameters and their effect on sound speed and species distribution at different water depth profiles in three regions of L. Albert.

- To compare the echogram visual display of fish backscatters of lakes Victoria and Albert, Uganda, with a 120 kHz frequency.
- To characterise the acoustic backscattering properties of major fish species in different regions of L. Albert using acoustic data of 2021 survey, Uganda.
- To map the Nautical Area Scattering Coefficient (NASC) averages of the acoustic categories of L. Albert.
- To map the fishing areas and fish species landing proportions in three regions of L. Albert, Uganda.

### **1.5 Research hypotheses**

- (i) The sound speed does not change at different water profiles and across three regions of L. Albert.
- (ii) The distribution of fish species targeted in three regions of L. Albert does not vary.

### **1.6 Significance of acoustic study in L. Albert**

The fisheries of L. Albert are experiencing dynamic changes in fish stocks, fish catch, and ecosystem diversity. Several fish stock assessment attempts have been undertaken in L. Albert, although with limitations to fisheries dependent information (catch landings, fishing effort, fishery socioeconomics). The present study focuses on establishing an acoustic sampling protocol for L. Albert, the first-ever implemented hydroacoustic survey of this lake. The development of acoustic survey protocols requires a critical understanding of fish biology, behavioural characteristics, species distribution, and environmental parameters in different regions of the lake. Therefore, species composition, acoustic backscatter categories, relationships of NASC, sound speed, and Nile perch catches were evaluated. The acoustic backscatter energies on echograms are always verified through fishing experiments, that is, trawling, target fishing for catch composition, fish biology, behaviour, and water environmental effects on acoustic intensities for precise estimation of fish densities and biomass. Fisheries acoustic technology and research provide detailed information on fish biomass and density distributions to understand biodiversity and ecological functioning. Therefore, this information helps to guide appropriate fisheries management guidelines for fish stocks, fisheries activities, and other developments, such as the oil and gas industry which might affect fisheries.

## 2 LITERATURE REVIEW

Fisheries acoustic methods of fish stock assessments are reported to be efficient in exploring large areas of water in a short period of time with high spatial and temporal resolutions (Thayne, 2016; Higginbottom, 2009). Initially, hydroacoustics were limited to marine environments, however, subsequent improvements in acoustic instruments such as use of EK80, Large Scale Survey System (LSSS) and portable echosounders. These recent modifications have helped improve acoustic data acquisition, processing, analysis, and reporting which has made fish stock assessment with acoustics provide the precise fisheries status and modal trends to guide resource managers. In water systems such as Lake Victoria, acoustic information from these surveys has guided the development of sustainable fisheries management measures (Proud et al., 2020). Within the last two decades, several acoustic surveys have been successfully conducted by NaFIRRI in L. Victoria to estimate the abundance, biomass, and distribution of exploited fish stocks (Kayanda et al., 2012). In addition, several studies have been conducted on lake bottom strata, sediments, and bathymetric mapping of lake bottoms using hydroacoustics (Inigo et al., 2013; Hamilton et al., 2022) in lakes Victoria and Albert in Uganda. The first bathymetry survey in L. Albert in August 2020 described and designated lake strata which were georeferenced into survey transects (Hamilton et al., 2022). Therefore, the first-ever acoustic survey in L. Albert was conducted in September 2021. While the basic acoustic and theories are known, each aquatic ecosystem requires the development of a standardised sampling procedure (Getabu et al., 2003; Hsueh-Jung et al., 2011). Therefore, in L. Albert, there is no standardised recipe for conducting an acoustic survey, and being a multispecies fishery system, there could be variations in target species which might differ in distributions in the water column. However, the two systems, Lake Victoria and Lake Albert, have some common species (the Nile perch and small pelagics) with detailed acoustic information and standardised operating procedures for Lake Victoria (Inigo et al., 2013; LVFO, 2018). Such related species and information will be used as a baseline for future L. Albert acoustic studies. Acoustic techniques are supplemented by biological information, trawl surveys, and ecological characteristics. Nile perch and silver cyprinid fish of L. Victoria possess swim bladders, which are the most important fish organs for reflecting acoustic sound waves. Therefore, these target species can reflect sound waves transmitted from the acoustic transducer in a similar manner in both lakes (Proud et al., 2020). A range of other methods are also available to estimate the spatial and temporal distribution, size structure, and density of fish species. The most widely used methods include gill netting experiments and seining; however, these methods are very limited in spatial coverage and require greater effort in terms of money and time (Jurvelius et al., 2011).

### 2.1 Fisheries hydroacoustics

The application of hydroacoustics in fisheries studies enables faster, real-time data acquisition from large survey areas (Simmonds and MacLennan, 2005; Georgakarakos et al., 2011) without interrupting fish species and their ecological habitats while collecting data. However, fish trawling or target fishing experiments are required to verify and describe fish echoes during the interpretation and estimation of fish density and biomass from hydroacoustic data (Jurvelius et al., 2011). Hydroacoustic assessments are applied in a wide range of aquatic habitats, such as marine and freshwater ecosystems, rivers, and reservoir dams (Medwin and Stanton, 1999). The use of hydroacoustic technologies in aquatic ecosystems has been vital in fish stock assessment studies in L. Victoria; for example, information on spatial and temporal trends of fish biomass and density distributions is available. The implementation of hydroacoustic surveys in L. Victoria has been ongoing for the last two decades, involving a series of acoustical studies on

major exploited fish species. The biomass and distribution of Nile perch, Daaga, and haplochromines are reported to span the lake profile and constitute exploited stocks of trophic importance to the ecosystem (Taabu-Munyaho et al., 2013). Hydroacoustics combined with trawls and environmental sampling of water provide information relevant to explaining fish distributions, species composition, and population structure.

Hydroacoustics covers a wide area in a short period of time, thus allowing large spatial scales to be studied, making it efficient in sampling highly migratory and mobile fish species (Korneliussen et al., 2016). Thus, the quick acquisition of fish acoustic signals is a time saving and more cost-effective method than other alternative fish stock assessment methods. However, hydroacoustic studies require detailed fish species information, such as fish biology and behaviour, water ecology, and species composition and size structures (Barange et al., 1996). Such information clearly guides scientists in assessing fish densities and biomass and harmonising the sampling protocol for data collection and analysis. In addition, with hydroacoustic information, scientists and other fisheries stakeholders can develop models for fisheries management and sustainable exploitation of resources (Sayer et al., 2018). In the case of L. Albert, the existing management measures are based on a precautionary approach which sometimes challenges managers and scientists owing to data limitations and scant information on fisheries.

According to Wandera and Balirwa (2010), different fish species inhabit different lake habitats. Catch rates from different landing sites can be used to collate and reference fish distribution and density. However, fishery-dependent data, catch landings, and fishing effort in L. Albert have limited information on species composition, biology, and fishing grounds. In fisheries hydroacoustics, fish species target strength (TS) and length-weight relationships are required to convert the volume backscattering strength ( $S_v$ ) to absolute biomass (Simmonds and MacLennan, 2005). It measures the reflection coefficient of a sonar target (fish) and is usually quantified in decibels (dB). Fish TS has been studied using several methods, either *in situ*, *ex situ*, or laboratory experiments, to develop mathematical models for TS from the backscattering coefficient characteristics of target fishes (Kim et al., 2018). Hence, the precision of TS information is the key scaling factor that determines the accuracy of biomass estimates and, consequently, the appropriate management of stocks (Kayanda et al., 2012).

The mean target strength is usually expressed in linear relationship between  $TS$  (dB) and fish length ( $L$  in cm) as in equation below,

$$TS = a 20 \log(L) + b \quad (1)$$

where  $a$  is the slope,  $b$  is the intercept of the regression, and represents the TS of the hypothetical length of fish,  $L = 1$  cm.

The transmitted acoustic signals are reflected by the fish swim bladder or hard tissues to visualise fish schools or large fish targets in the water column. Other species utilise other gas-filled organs that can reflect sound waves, depending on the density differences between the gas and the environment (Kim et al., 2018).

In acoustics, the important parameter, the area backscattering coefficient ( $S_a$ ), is a measure of the acoustic energy returned from a water layer between two depth intervals. It is obtained from ( $S_v$ ) which is the average scattered energy in the water volume with a range of intervals and pings in the water column. The scattered acoustic energies are integrated per square meter of the layer surface, thus the spherical area scattering coefficient ( $\sigma_{sp}$ ) and the nautical mile = 1852 m. Hence, the conversion formula is as follows:

$$S_A = 4\pi(1852)^2 * S_a \quad (2)$$

where  $S_A$  is also known as NASC (Simmonds and MacLennan, 2005). In this study, the NASC was processed in the LSSS to estimate and map fish NASC in different regions and depth strata.

TS varies depending on the presence of the swim bladder, fish size, behaviour, morphology, and physiology of fish, the aspect angle at which the signal hits the fish, and the tilt angle to the transducer (Ross et al., 2013). To estimate the actual TS of fish, the echoes received are dependent on the position of the fish in the beam (Simmonds and MacLennan, 2005). The fish position, fish size, and school influence the backscattering intensity (Simmonds and MacLennan, 2005). However, this study did not estimate the target strength of fish species because of the limitations of biological sampling and the required logistics. Estimating fish density and biomass will be a major goal for future studies and trawl surveys.

### 3 MATERIALS AND METHODS

#### 3.1 Study area and scope

The hydroacoustic and environmental water studies were conducted around L. Albert in the Uganda portion, with a total surface area of about 2850 km<sup>2</sup>, from 22<sup>nd</sup> to 28<sup>th</sup> September 2021. This study focused on establishing a hydroacoustic survey protocol for the major L. Albert species to improve fish stock assessment methods. The cruise track followed perpendicular bathymetric transects, which were divided into three zones (northern, N; central, C; and southern, S). The southern zone stretched from Ntoroko-Mulango to Kikuube-Usua, the central zone from Kikuube-Usua to Buliisa-Wakii, and the northern zone from Buliisa-Waaki- to Pakwach-Dei B which were further clustered into Inshore, Coastal and Deep depth strata.

#### 3.2 Cruise design

The cruise track for L. Albert was developed using QGIS version 3.16 (Figure 1). Along the pre-designed transects in each region, water depth ranges were used to cluster the lake profiles into deep, coastal, and inshore. All transects were mapped only on Uganda's side of L. Albert because the survey logistics were limited to cover Uganda's side of jurisdiction. The intersection points are described using numbers 001 to 196 (Figure 1) to guide cruise navigation during data collection. The cruise track was formed by perpendicular transects (28) each approximately 25 nautical miles (nm), joined by 17 dead heads of approximately 5 nm. The data recording range was set at 120m, which was implemented along the cruise track at a vessel speed of 9–10 nm.

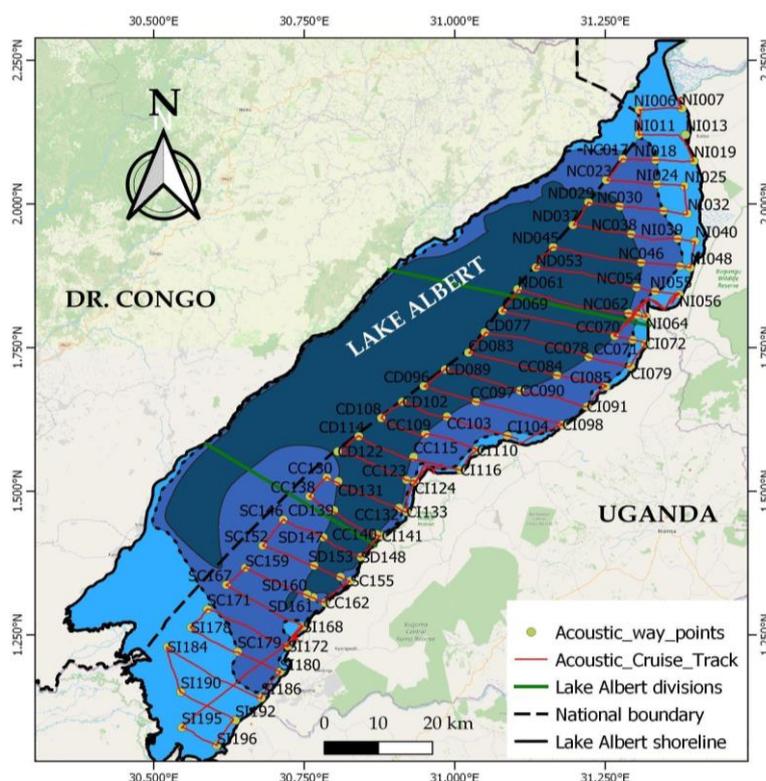


Figure 1. Acoustic transects and cruise track during data collection in L. Albert in Sept. 2021. Depth ranges:  $\leq 20\text{m}$  (I, inshore),  $20\text{--}40\text{m}$  (C, coastal) and  $> 40\text{m}$  (D, deep).

### 3.3 Environmental water sampling

Water samples were collected at selected inshore (100 m from the shoreline) and offshore points (any other distance beyond inshore) along the previously established hydroacoustic cruise track between September 22<sup>nd</sup> and 28<sup>th</sup>, 2021, simultaneously with the hydroacoustic data collection. The water sampling boat closely followed the acoustic boat while navigating the three regions of Lake Albert. Three water samples were collected randomly according to the number of established transects per region and the water depth (Figure 1). Water samples were obtained from approximately 0.5 m depth using a 2 L Van Dorn water sampler (Myers, 2002), and the location was recorded using handheld GPS equipment. Water samples were temporarily stored in a cooler box to ensure that they remained in their original state. Vertical sampling of the water profile (*in situ* measurement) of the water physicochemical parameters was performed using a YSI EXO multi-parameter probe. The samples were collected at depths between 2 and 40 m. The water parameters recorded included hydrogen potential (pH), dissolved oxygen (DO), temperature, electrical conductivity (EC), turbidity, and salinity. The total depth at each hydro station was measured using an echosounder. Secchi depth (SD) (i.e. the maximum depth of water column clarity) was recorded. In the laboratory, water samples were filtered using a 0.45  $\mu\text{m}$  filter to separate dissolved and suspended organic matter (Myers, 2002). A known volume (200 ml) of water samples was filtered using filter paper to analyse other parameters such as chlorophyll-a, which was reserved for a different study on soluble nutrients.

### 3.4 Acoustic data collection

The research boat was docked at the Kaiso landing site (Central region), and three days were spent preparing for the excursion. The installation and calibration of the echosounder were conducted between September 20<sup>th</sup> and 21<sup>st</sup>, 2021. Calibration was conducted at a water depth of 20 m, following the standard calibration protocol (Foote et al., 1987). The pole was used to suspend the three lines approximately 1 m off the vessel, while the lines passed through a small loop on a metal wire (Figure 2a). The standard target was a 23 mm diameter copper sphere with TS = - 40.4 decibels (dB) at 120 kHz at the start of the hydroacoustic survey (NOAA, 2023). The sphere was suspended on three monofilament nylon lines and held at a depth of 5 m below a 120 kHz transducer, which was mounted on the port side of the research vessel. The equivalent two-way beam angle and theoretical TS of the sphere were calculated. During calibration, the depth profile average temperature was collected using the YSI EXO multi-parameter, and the sound speed was set to 1503.6 m/s. The salinity was initially assumed to be zero. A CTD probe was used to record water parameters (temperature, depth, and salinity) along the survey transects at different hydrostations.

Data collection started on the 22<sup>nd</sup> until the 26<sup>th</sup>, which was spared as a resting day to replenish the field logistics, then resumed on the 27<sup>th</sup> until 28. The acoustic data were recorded using a Simrad EK80 scientific echosounder and a Broad Band Transceiver (BBT) operating in narrowband mode with a split beam transducer at 120 kHz frequency at a nominal beam width of 7 °, mounted at the port side of the Nkejje fibre boat (Figure 2). The transducer depth was set at 1.0 m below the boat, and the acoustic recording was detected at  $\geq 5\text{m}$  below the water surface up to 0.2 m above the lake bottom. Acoustic data were collected during the daytime from 8 am to 6 pm, adopted from the acoustic standard operating procedures for L. Victoria (LVFO, 2008). The vertical beaming of the transducer was performed while recording acoustical signals along the survey transects at a boat speed of 9–10 nm.

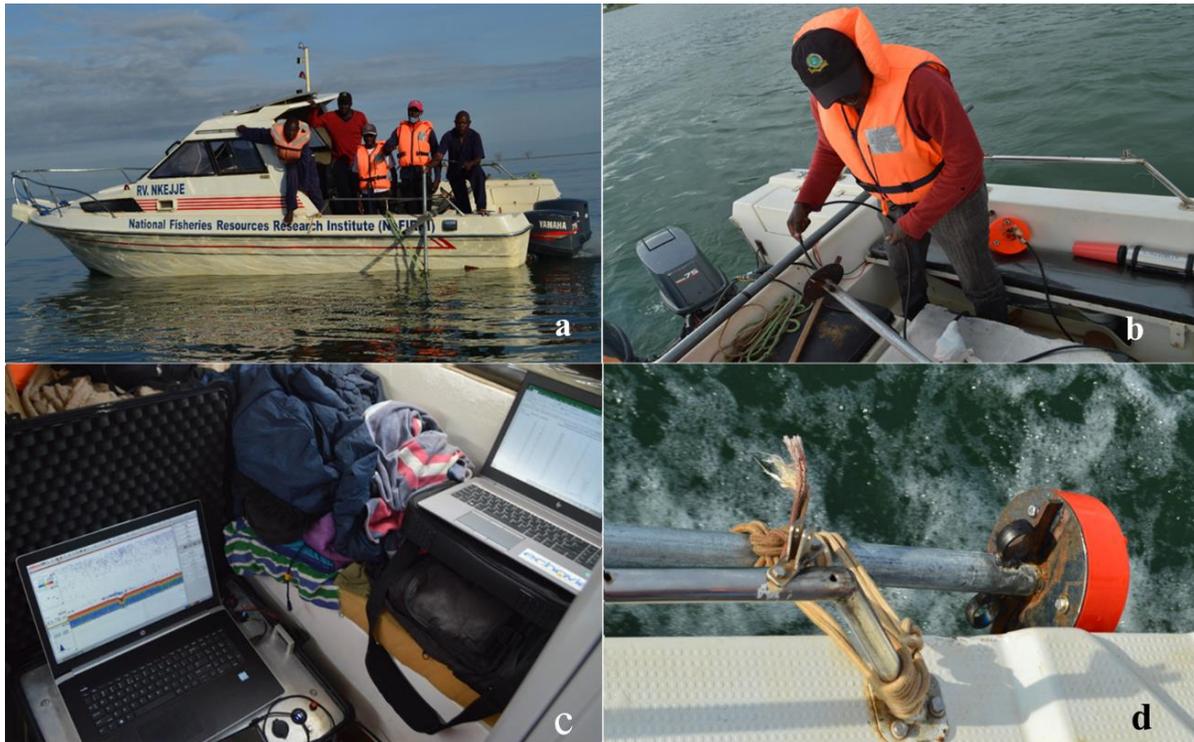


Figure 2. Acoustic system setup on Nkejje Research vessel during the baseline survey. System setup (a and d), deployment of the transducer (c), echogram display during data recording, and (d) general-purpose transceiver and data recording laptop (c). (Photo credit: Evarist N.)

### 3.5 Fish landings and fishing areas

Catch assessment surveys (CAS) archived data and information were retrieved from the National Fisheries Resources Research Institute (NaFIRRI). The retrieved data and information were available for all the major landing sites. Data on the type of fish species and landed catch per landing site were retrieved. CAS studies involve measuring and recording species catch, catch composition, species type and numbers, weight (kilogram, kg), Total Length (TL), or fork length (FL). Fishing effort details such as boat type and numbers at each landing site, days fished in a week, number of fishers, fishing gear type, units and mode of operation, fish revenue, and fishing duration are noted (NELSAP-CU, 2021). These data sets and information were used to cluster species composition, landings, and proportions of each species at each landing site and region for abundance estimates. The fish species size population structure was presented for the major targeted species.

Information on the species fishing locations and characteristics was retrieved from the Uganda Freshwater Biodiversity Portal (NARO, 2023). In addition, information on the species, ecological, and habitat distribution of *E. bredoi*, *B. nurse* (Nakiyende et al., 2022), and *Lates* spp. was collected during the darkness (new moon phases) of the peak fishing seasons in 2021. Fisheries locations were marked using handheld Geographical Position System (GPS) equipment, and water depth was recorded with a portable handheld echosounder. The generated information was used to map the fishing locations of the major target species. Fishing areas were based on locations where fishing boats, lights, and gears were set during fishing activities in different seasons. The fishing locations were overlaid with the acoustic survey transects.

### 3.6 Data processing and analysis

#### 3.6.1 Baseline on visual display of backscattered intensities of 70 and 120 kHz frequencies in L. Victoria

The L. Victoria raw hydroacoustic data were loaded into LSSS, version 2.14 (Korneliussen et al., 2016), and the echogram interpretation was carried out at resolutions between 5 and 10 nm. The near field for L. Victoria hydroacoustic data was set at 10 m because the two transducers were inbuilt into the hull of the research vessel. The L. Victoria hydroacoustic data pre-tested in LSSS, had been collected in September-November 2021 in the entire L. Victoria. The visual interpretation of echograms and backscattered energies of 70 and 120 kHz were compared to evaluate the threshold for categorising Nile perch and small pelagic fish species. This was easily conducted with L. Victoria acoustic data because they were collected using two frequencies, and acoustic information for the fish was known. A -72 and -60 dB difference was used to assign small pelagic backscatter, as in (LVFO, 2018). The thresholds below -72 dB were likely echoes from zooplankton by comparing the echogram of the frequency response method 70 and 120 kHz for the 2021 acoustics data from L. Victoria.

The observed differences in the appearance of the echogram display of the two transducers were used to benchmark the minimum and maximum response values assumed to be from fish echoes of single targets and fish schools and eliminate noise and echoes from zooplankton (Tumwebaze et al., 2007; LVFO, 2018). The threshold range of -72 dB was used to remove weak backscatter regarded as echoes from zooplankton (assumed to be freshwater shrimp), as these aquatic organisms are reported to exist in both lakes Victoria and Albert (Li et al., 1999; Goudswaard et al., 2006).

#### 3.6.2 Processing of L. Albert hydroacoustic and water environmental data

The raw hydroacoustic data of L. Albert were loaded into the LSSS, and echogram interpretation was performed at resolutions between 5 and 10 nm. The following adjustments were made in the LSSS: the near field was set at 5 m (depth of the initial top boundary) to consider the transducer depth. The ping mapping used was at a distance of 120 kHz, and the preferred upper and lower thresholds were set at -30 and -72 dB, respectively (Figure 4). The lake dead bottom (detected lake bottom) was set through automated synchronisation 0.5 m off the bottom from the lower boundary threshold. The detected bottom line was edited and aligned above the lake bottom by fixing the noise spikes (Appendix 6). Fish echo evaluation on the echogram was performed through visual examination of key regions with possible areas of fish schools and high backscattering intensities (Appendix 2). Visual inspection of the TS distribution, Sv distribution, and threshold responses of such marked areas were assessed visually and compared in the top and bottom layers by adjusting the lower and upper integration thresholds (Appendix 2). Fish backscatters in this range were temporally selected with a rectangular box and cross, and based on event log information, the echoes were verified to determine whether they were emitted by fish or other aquatic organisms (Korneliussen et al., 2009). The echogram regions with high backscatter intensities were checked to remove interference noise from the water environment (Appendix 3).

The water temperature and salinity were used to calculate the sound speed for each hydrostation and the water depth profile for the entire surveyed area. During data processing, the function water parameters file was loaded into R studio (version 4.2.2), and the package 'oce' was used to estimate the sound speed from water temperature, salinity, and water depth (Kelley, 2018).

The average sound speed (see table in Appendix 1) was incorporated in the LSSS and used to correct the NASC values for all water zones (Inshore and Offshore) in the three regions.

### 3.7 Manual scrutiny categorizations assumptions of hydroacoustic study of Lake Albert

The manual scrutiny category (MSC) categorisation method was used (Korneliussen, et al., 2016). Being the 1<sup>st</sup> acoustic survey in L. Albert, the manual categorisation of acoustic backscatter energies was used based on the threshold difference method as follows:

- 1) The four assumed acoustic categories were Nile perch (Perch), small pelagics (PEL1), other demersal fish (ODFI), and other species (OTHER), as defined in the ICES LSSS database.
- 2) The backscattering intensity of any threshold intensity at -60 dB and below was assumed to be Nile perch. This assumption is based on the Nile perch acoustic backscatter properties at 120 kHz in L. Victoria (Kayanda et al., 2012).
- 3) The backscattering intensity of small pelagics (Pelagic 1). These could be assumed to be in the same size range as the Daaga fish of L. Victoria, with a threshold intensity of -72 dB (Tumwebaze, 2003, Tumwebaze, et al., 2007).

### 3.8 Manual interpretation of echograms

The backscatter data in all connecting lines (Dead Head regions; DH) and near-surface noise spikes were marked and excluded. Examples of echo traces of noise interference regions were bottom echoes, intersection transects, noise spikes, and regions of bad acoustic data (transducer default data) were all excluded from regions to be categorised. The remaining parallel transect lines consisted of backscatter echoes to be categorised. According to Korneliussen et al. (2016), fish categories are grouped in LSSS by the operator visualising assigning regions with similar acoustic properties. Some fish species appear as single targets, while others aggregate, such as schools, and sometimes in specific water depth layers. Marking regions and layers of similar acoustic properties were selected and categorised into the following: Nile perch (Perch), small pelagics (PEL1), other demersal species (ODFI), and other species (OTHER) (Appendix 2). The categorisation of Nile perch was based on a threshold difference between -72 and -60 dB integration threshold frequency, as adopted from L. Victoria acoustic studies (Tumwebaze et al., 2007; Kayanda et al., 2012). The remaining categories (PEL1, ODFI, OTHER) were classified by the differences between -72 and -60 dB, and the balance  $S_A$  was estimated for the respective fish category, provided that the total  $S_A$  was 100% per layer. Manual characterisation of the acoustic categories was based on the depth distribution of the acoustic backscatter layers; that is, PEL1 was defined in the upper layer (depth range from 5 to ~20 m), and other species were identified in the middle layer, between ~20 and ~40 m, and the lower layer, defined as close to the lake bottom (>40 m), was classified as other demersal species.

The proportion (%) of each acoustic category was stored for every 0.05 nm. The results were stored as text notepad files, including the survey frequency, latitude and longitude, water depth, longitude and latitude, and time of data recording of acoustic backscattered according to the respective acoustic categories. The acoustic fish categories were calculated as NASC in  $m^2/nmi^2$  at every 0.05 nm integration interval. These were integrated into box grids of latitude 4 nm by longitude of 4 nm for the surveyed area. The NASC average for the four fish categories and their distributions in the box grids were mapped for the entire surveyed area.

### 3.9 Statistical analysis

The analysis of all the data in this study was performed using R studio (version 4.2.2) with different packages depending on the datasets and results required. The Shapiro-Wilkoxon test was used to test the normality of salinity and temperature data collected at different hydrostations. The sound speed in water was calculated from the temperature and salinity data collected in different zones and regions. Refer to Section 3.6.2 for the processing of water environmental data. An ANOVA test was used to show the variance in sound speed between the zones and regions of the sampled hydrostations. A report with text notepad files from the echogram for different water depths was generated. The fish acoustic backscatters were calculated as NASC averages, and the results for the four fish categories and total NASC in  $\text{m}^2/\text{nmi}^2$  were estimated for each region and water depth profile. The 4 nm by 4 nm box grids were used to map the NASC averages ( $\text{m}^2/\text{nmi}^2$ ) for each fish category along the parallel survey transects. The proportion (in %) of landings was used to describe species abundance at each landing site and region.

## 4 RESULTS

### 4.1 Environmental characteristics and effects on sound speed at varying water depths

The physical parameters (Secchi depth, dissolved oxygen, water temperature, pH, and conductivity) varied across the three regions, with higher levels recorded in the inshore areas (Figure 5). Secchi depth (SD) ranged between 0.2 to 4.3m with the lowest being recorded in the northern region. Dissolved oxygen (DO) ranged between 4.0 to 8.2 mg/l, with the highest recorded (8.2 mg/l) in the inshore waters in the central region of the lake. The lowest DO levels of 4.0 mg/l were recorded in the offshore zone in the northern region. The temperatures ranged from 27.3 to 29.3 °C. Some hydrostations in the offshore zone of the northern region and in the inshore zone of the southern region registered slightly higher temperatures of 30 °C. The electrical conductivity (EC) ranged from 278.6 to 593.2  $\mu\text{S}/\text{cm}$ , and most of the sampled hydrostations registered high EC values. The pH values ranged between 8.0 and 10, indicating a generally moderate alkaline condition of L. Albert (Figure 3). The turbidity values ranged from 0.1 to 34.0 Nephelometric Turbidity units (NTU). The highest turbidity variations were observed in the north compared to other regions.

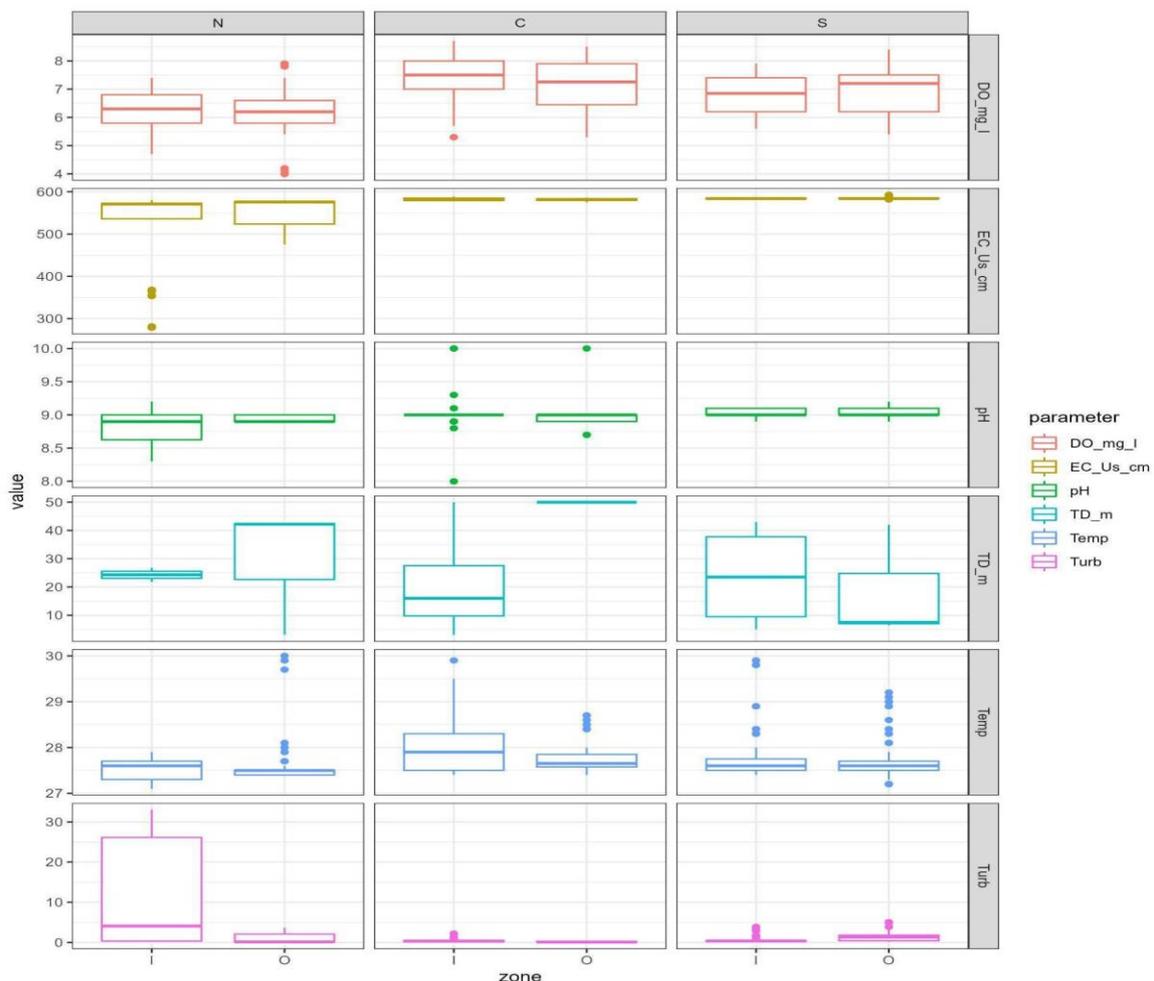


Figure 3. Water environment parameters from three regions (north, central, and south) and depth strata during the September 2021 hydroacoustic survey. Inshore (I): the distance of 100 m from the shoreline; Offshore (O): the rest of the lake area of  $\geq 100$  m; DO (Dissolved Oxygen, mg/l); EC (Electrical Conductivity, Us (cm)); TD (Total Depth, m); Temperature (Temp, in °C); Turbidity (Turb in NTU).

4.1.1. Effect of water temperature, salinity, and depth profile on sound speed in water

The water parameters salinity and temperature recorded at different water depths were used to estimate the sound speed at varying water depths (Figure 6; Appendix 1). The parameters in depth ranges from 0 (surface) to 1m were excluded, considering the transducer depth which was 1.0 m below the water surface. The salinity values ranged between 153.2 to 326.2 mg/l showing high variations in the central region compared to the other two regions. Variations in salinity were also observed within and among the three regions and zones. The salinities in the northern region varied from 153.2 300 mg/l, particularly in shallow waters <10 m. The general variability in salinity within the central region varied from 316 to 324 mg/l for both inshore and offshore waters (Figure 4). Water temperature generally varied from 27.3 to 29.3 °C in all three regions; however, the highest temperature (30 °C) was recorded in both northern and southern offshore waters at approximately 2 m (Figure 5).

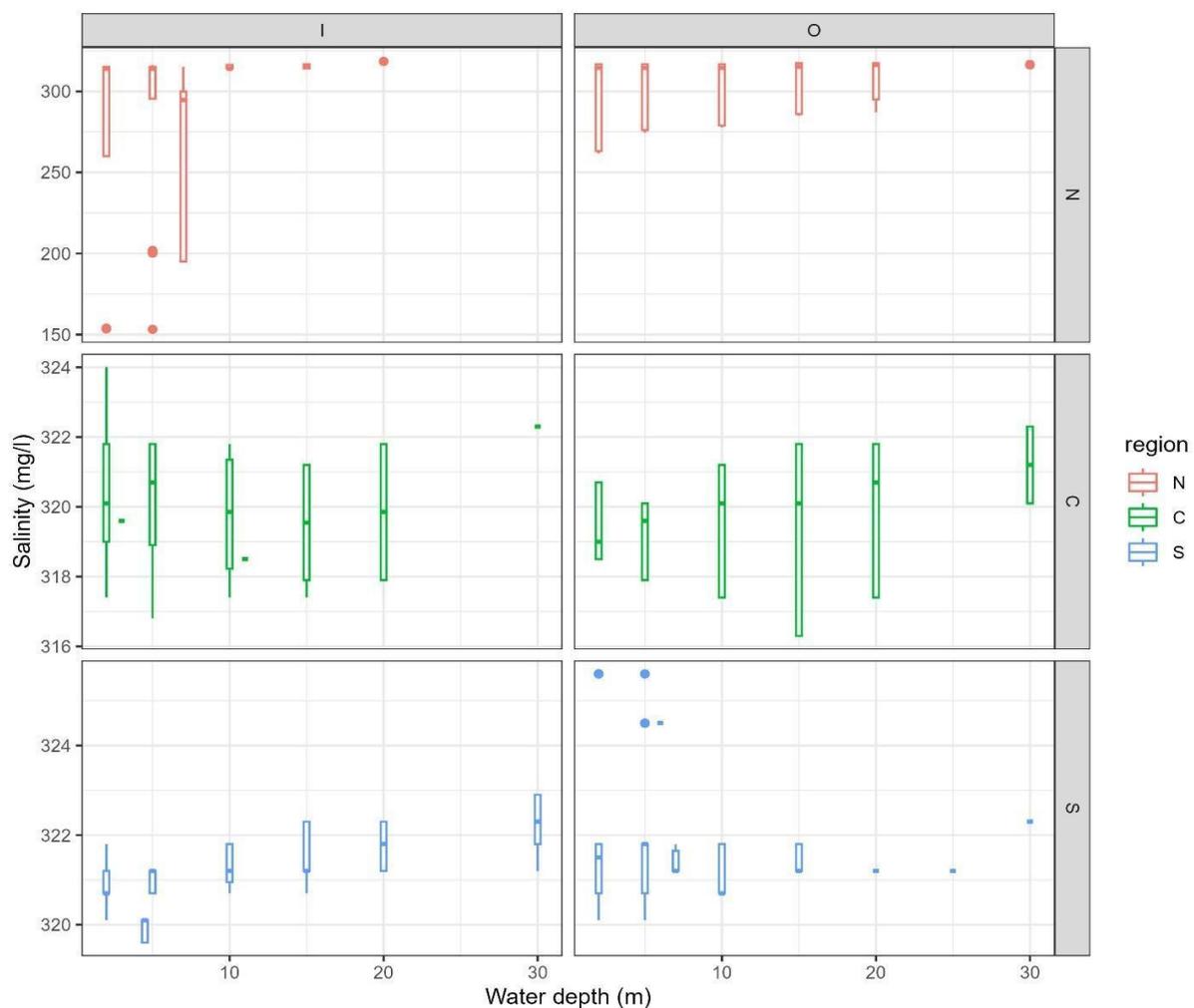


Figure 4. Water salinity (mg/l) variation with depth (m) in three regions and water zones.

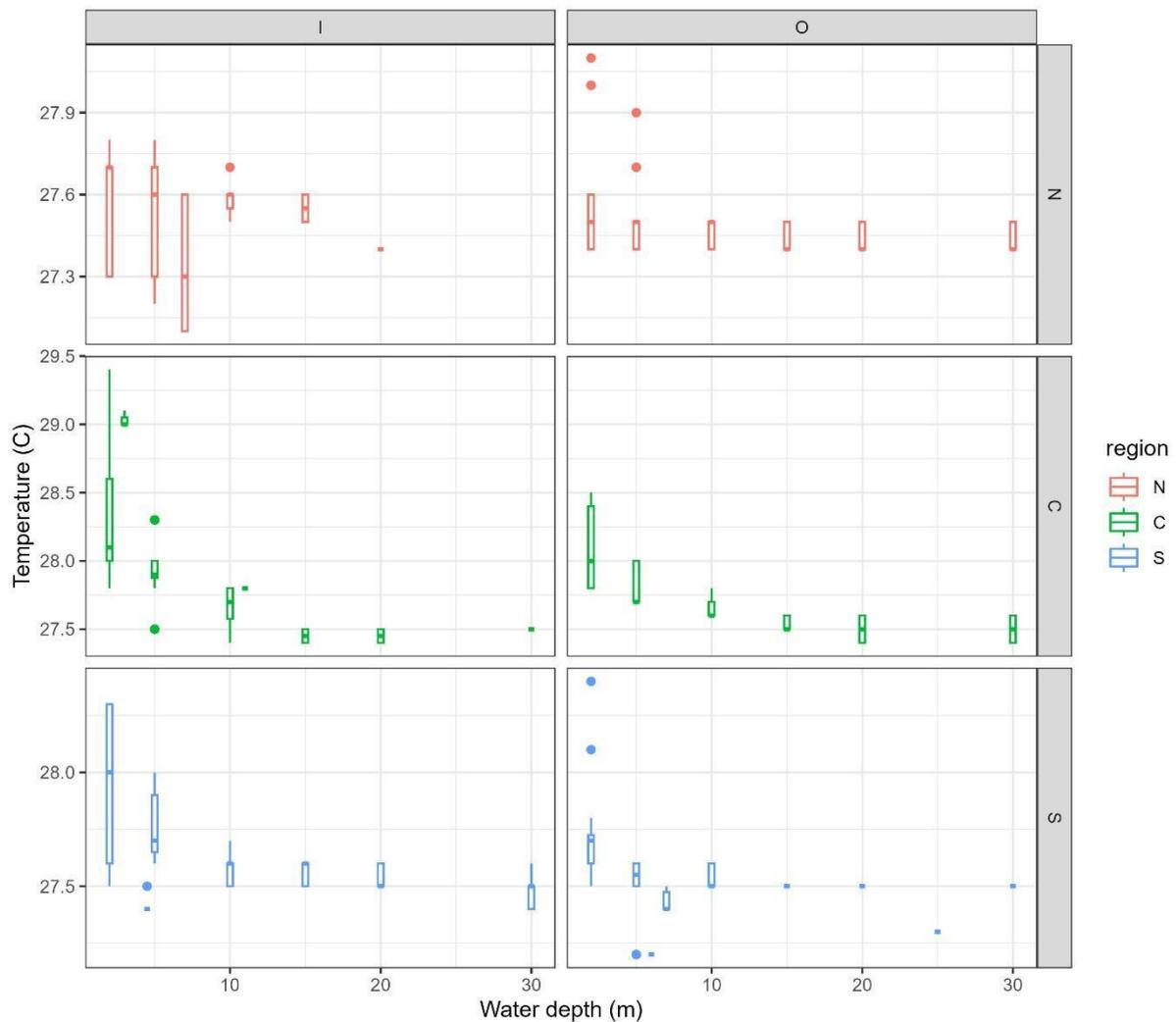


Figure 5. Water temperature ( $^{\circ}\text{C}$ ) variation with depth (m) in three regions and water zones.

The data normality was tested with the Shapiro-Wilcoxon test ( $W=0.34$ ,  $p=2.2^{-16}$ ). Generally, the sound speed varied with water depth; for example, depth ranges of 2–10 m showed higher variation in the inshore zone of the central region, while the least variation was observed in the offshore areas in the southern region (Figure 6). The average sound speed changed with salinity at different water depths. One-way ANOVA showed a significant difference in sound speed across zones and water depths (Table 2). The means of sound speed varied significantly in the inshore and offshore zones (Table 2).

Table 2. ANOVA statistical sound speed summaries across depth profiles and zones.

ANOVA summary of sound speed variation with water depth						
Df	Sum Sq	Mean Sq	F value	Pr(>F)		
Profile	1	67.8	67.76	59.57	6.49e-14	***
Residuals	498	566.5	1.14			
---						
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1						

ANOVA summary of sound speed variation in fishing Zones						
Df	Sum Sq	Mean Sq	F value	Pr(>F)		
Location	1	5.8	5.812	4.606	0.0323	*
Residuals	498	628.4	1.262			
---						
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1						

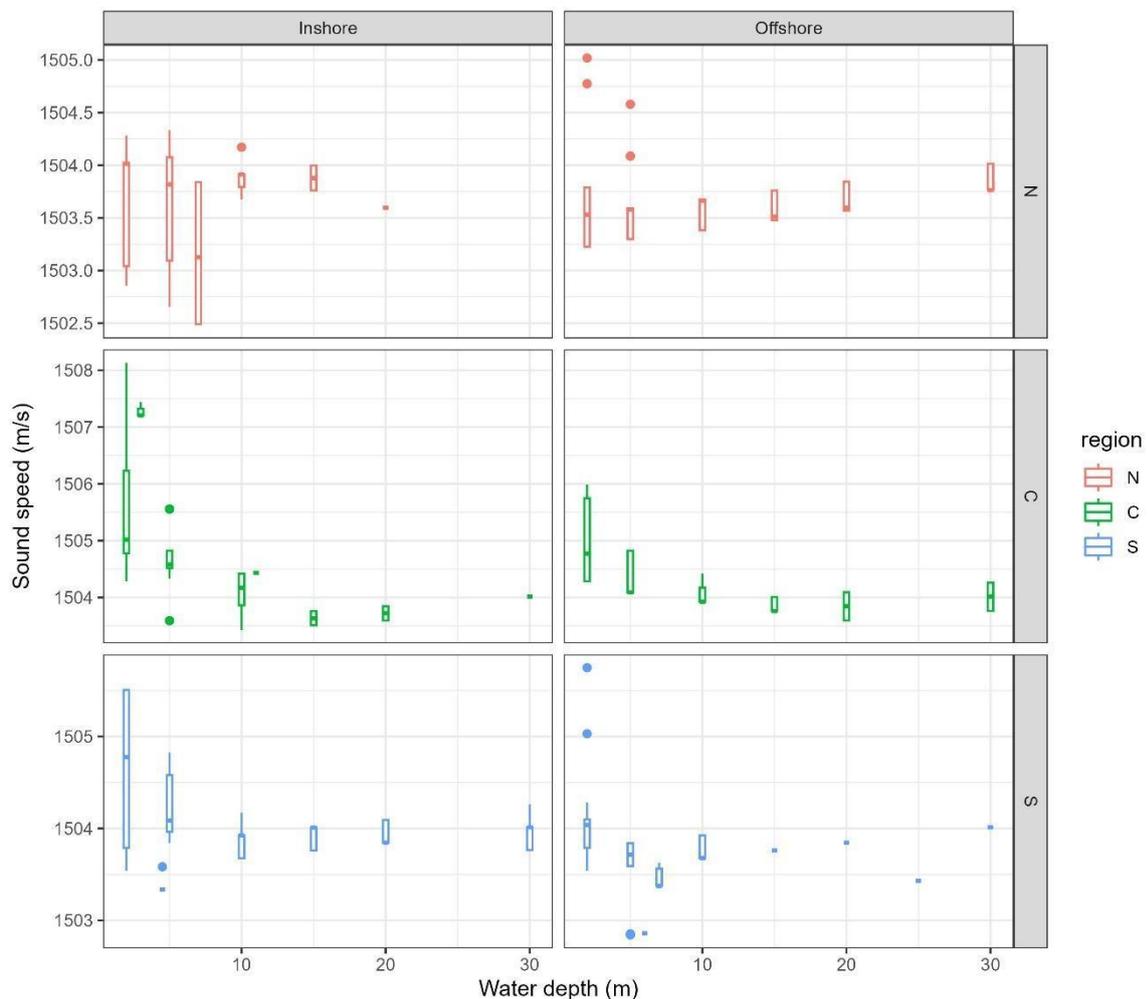


Figure 6. The distribution pattern of sound speed (m/s) at different water depths (m) of L. Albert, Uganda. Northern region (N), Central region (C), Southern region(S), Inshore (I): <100 m from the shoreline, Offshore (O): > 100m from the shoreline.

## 4.2 Backscatter characteristics of fish categories in different regions of L. Albert, Uganda

By generating correcting acoustic data using the sound speed estimated for each hydrographic region, we can evaluate that the total NASC was previously underestimated. Therefore, the newly calculated total NASC values were higher than the calibrated sound speed (Table 3). A difference in the total NASC ( $51,629 \text{ m}^2/\text{nmi}^2$ ) was noted between the corrected and calibrated sound speed.

Table 3. Total NASC averages and summaries of the entire survey when using the calibrated sound speed (1503.6 m/s) and corrected sound speed based on hydrographic regions (see Appendix 1).

Sound speed	Mean NASC ( $\text{m}^2/\text{nmi}^2$ )	Total NASC ( $\text{m}^2/\text{nmi}^2$ )
Calibrated	253.3	1,573,863
Corrected	261.9	1,522,234

Using the threshold difference method and the depth distribution of the acoustic layers, we were able to distinguish backscatter (see Method section). In L. Victoria, the fish acoustic backscatters were spread throughout the water depth, with fish schools observed at 1/3 of the water depth and near the lake bottom, whereas the L. Albert fish acoustic backscatter formed two distinguishable acoustic fish layers (Figure 7). Nile perch were observed as single targets, and Daaga as fish schools on the L. Victoria echogram. According to L. Albert, the first fish layer was observed at water depths of  $\leq 27 \text{ m}$ , and the second layer was observed at depths  $> 37 \text{ m}$ . However, in some regions, categorisation by layers was not possible, which interfered with species categorisation (Appendix 4).

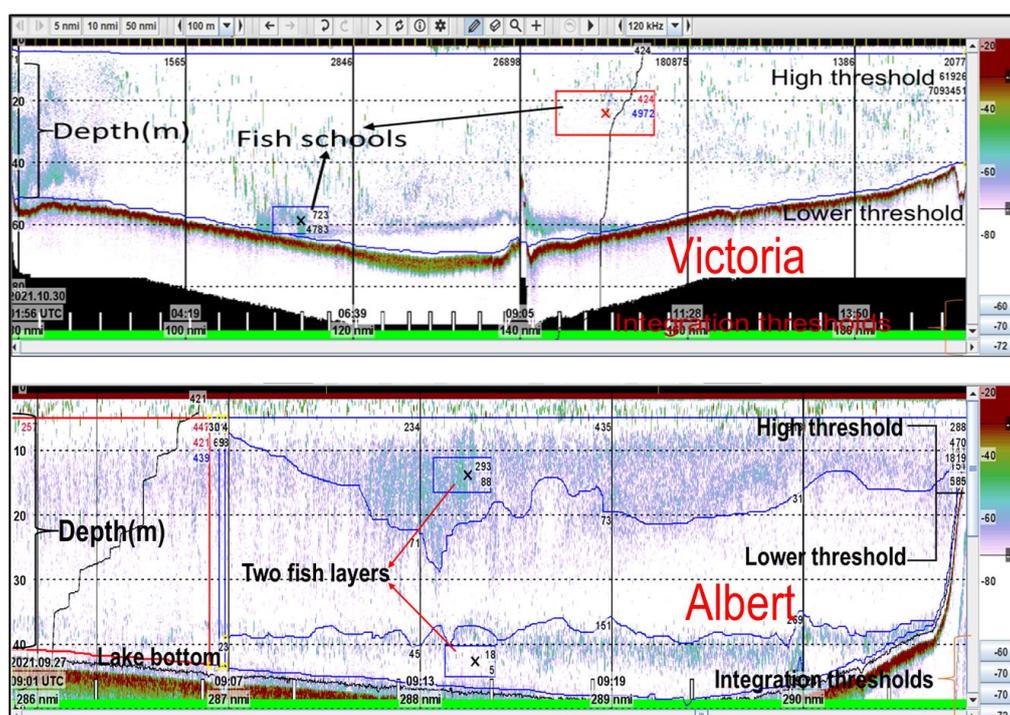


Figure 7. Echograms of lakes Victoria and Albert visual comparison of backscatters and fish layers September and October 2021 hydroacoustic surveys.

Four fish acoustic backscatter categories were classified: ODFI (other demersal fish species), OTHER (other fish species), PEL1 (small pelagic fish), and Perch (Nile perch). The highest NASC averages were recorded at an average water depth between 4 and 10 m. Nile perch had the highest FCR, followed by small pelagics, and the lowest was recorded for the other demersal fish category (Figure 8).

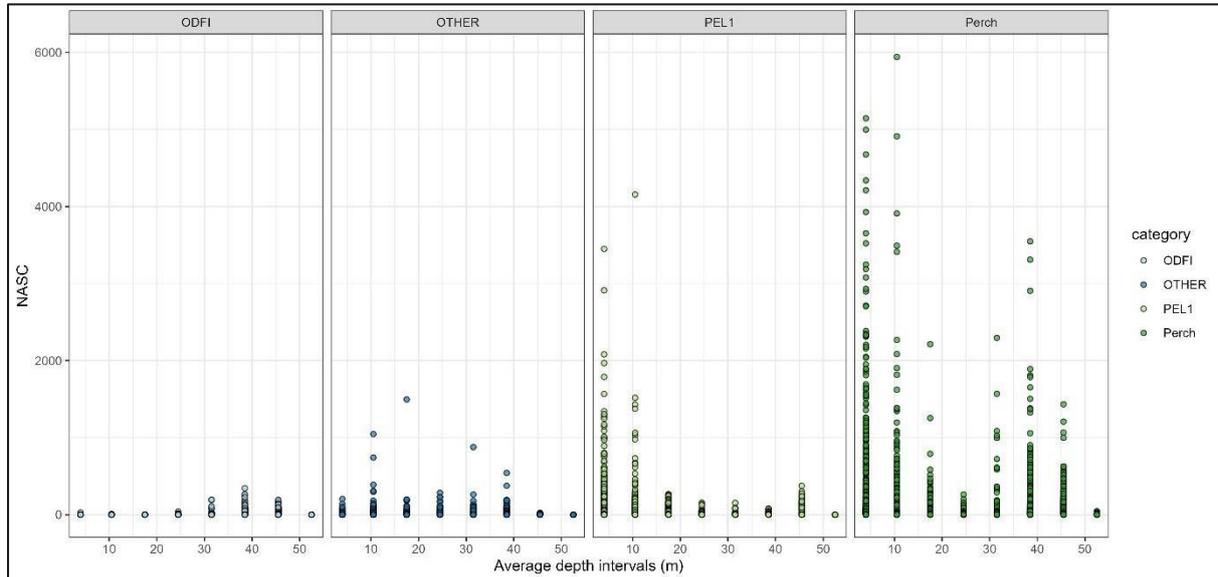


Figure 8. Variation in NASC ( $m^2/nmi^2$ ) of four fish categories (other demersal species, small pelagics, other species, and Nile perch) with depth (m) in L. Albert.

The Nile perch NASC averages were generally distributed over the three lake regions; however, box grids in the central region had the highest NASC averages, which were concentrated in deeper waters. Generally, the box grids around the inshore and part of the coastal zones had lower NASC averages (Figure 9). The Nile perch NASC averages ranged between 2 and 760  $m^2/nmi^2$  in the three regions.

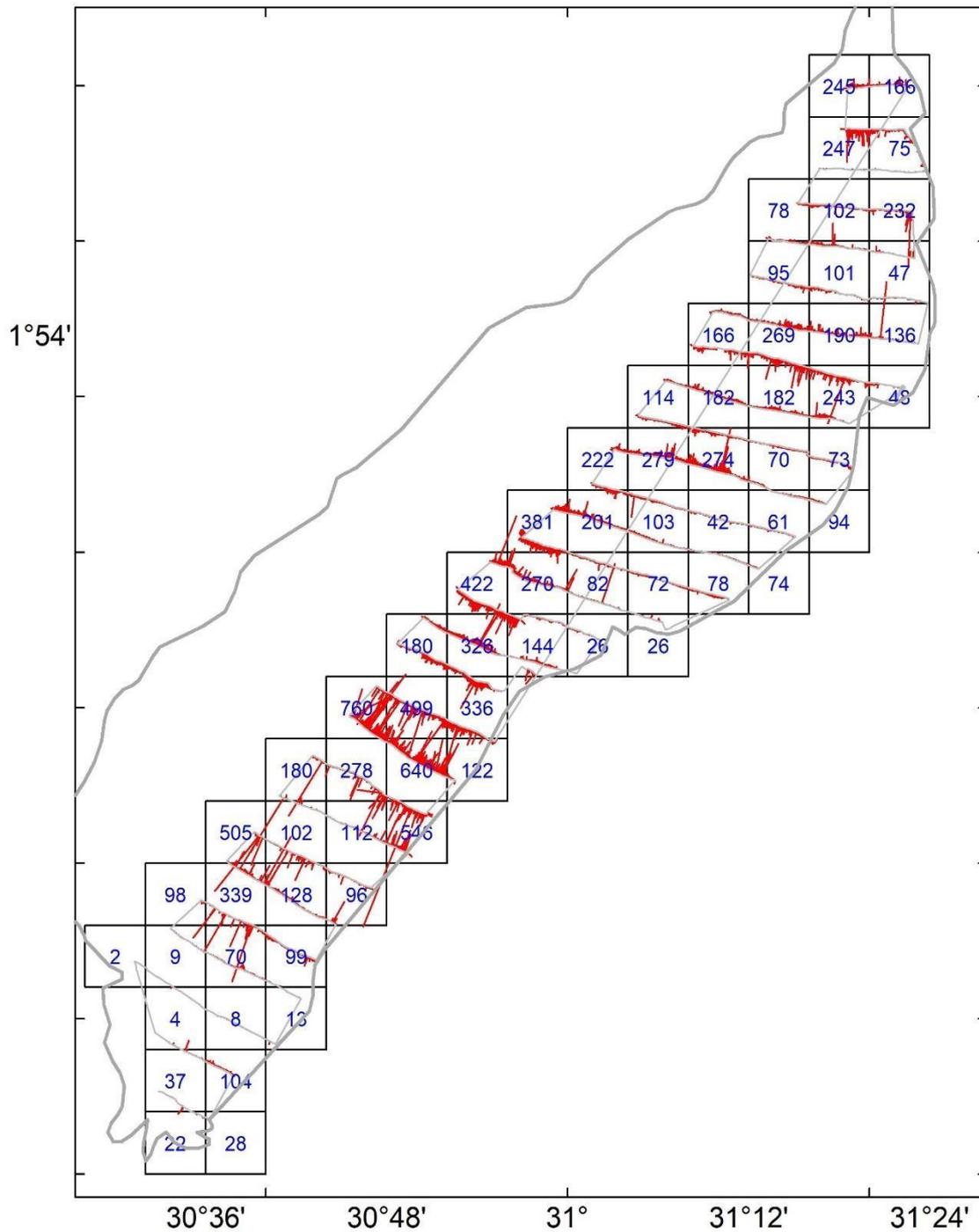


Figure 9. Nile perch (Perch) NASC ( $m^2/nmi^2$ ) distribution in 4 nm by 4 nm box grids in L. Albert.

The NASC averages for small pelagics were higher in the central and northern regions of the lake. However, box grids with the highest NASC densities were recorded in the central region (Figure 10). The NASC averages ranged between 4 and  $174 m^2/nmi^2$  in the central region. The box grids in the southern region had the lowest NASC averages.

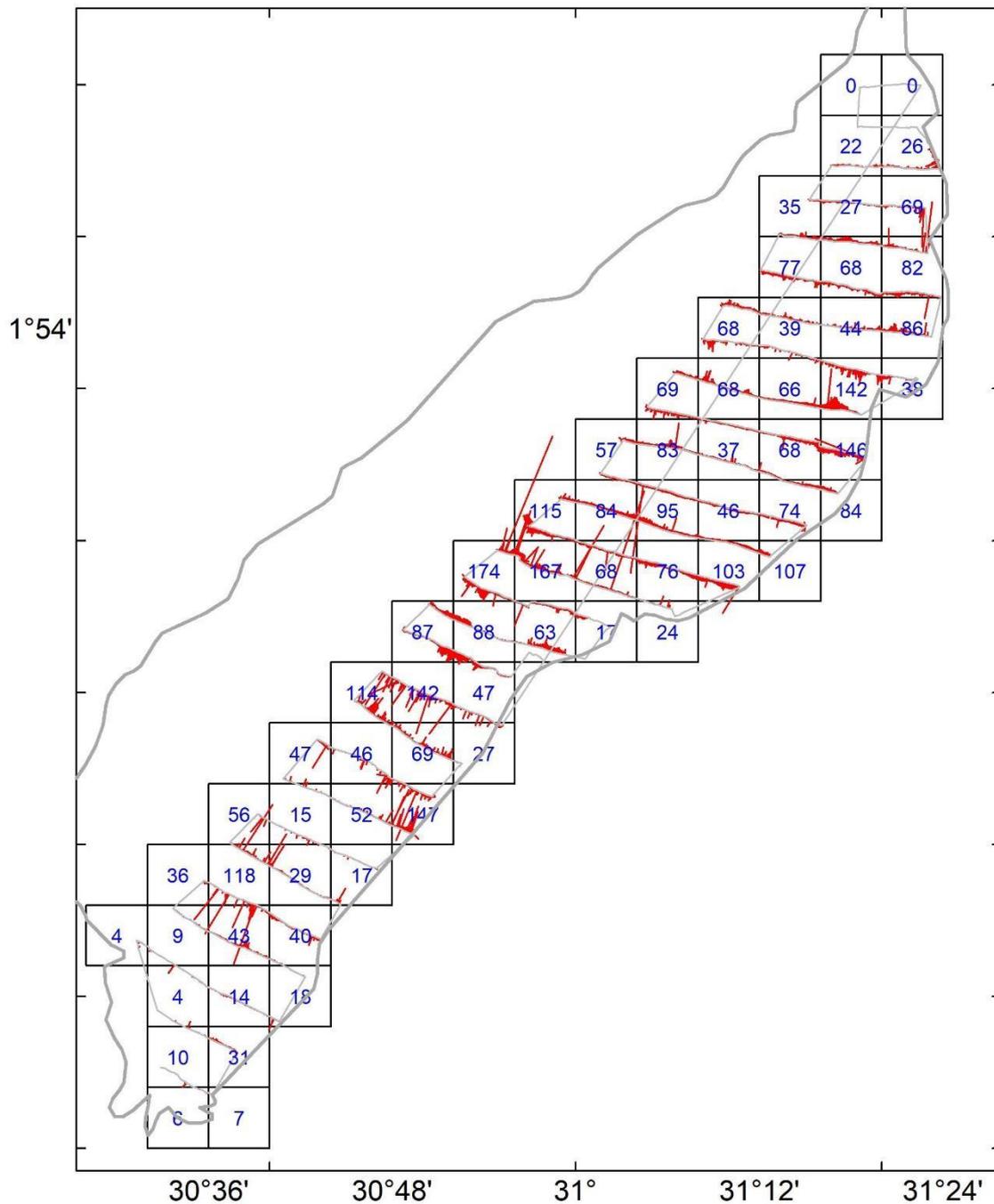


Figure 10. Small pelagics (PEL1) NASC (m<sup>2</sup>/nmi<sup>2</sup>) distribution in 4nm by 4nm box grids in L. Albert.

The NASC averages for Other Demersal fish (ODFI) were distributed in deeper waters of the central region, and compared to the other backscatter fish categories, their NASC values were lowest in the southern and northern regions (Figure 11). The NASC averages ranged between 1 and 49 m<sup>2</sup>/nmi<sup>2</sup> in the two regions. The box grids in the southern and northern regions recorded between 0 and 7 m<sup>2</sup>/nmi<sup>2</sup>.



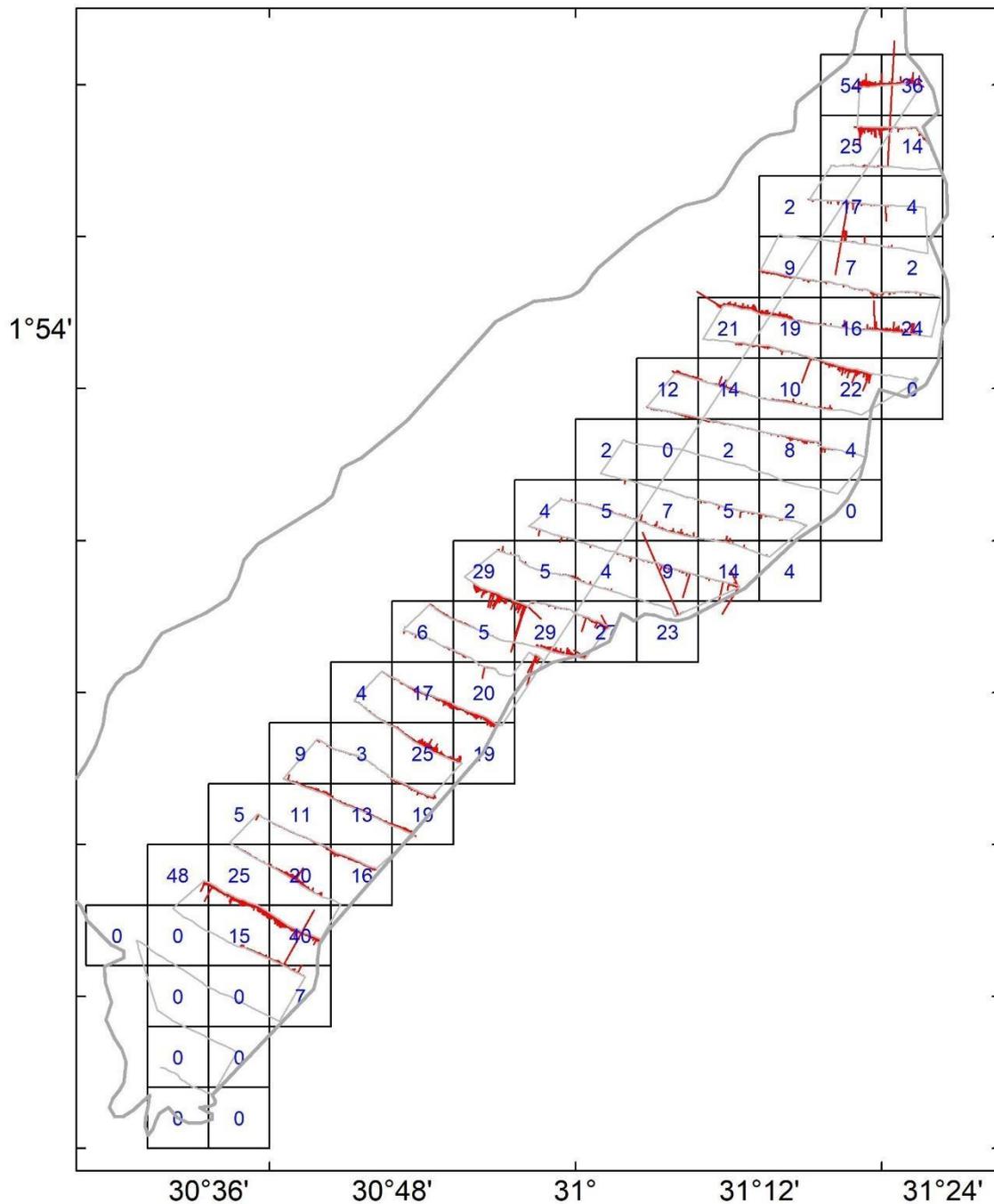


Figure 12. Other species (OTHER) NASC (m<sup>2</sup>/nmi<sup>2</sup>) distribution in 4 nm by 4 nm box grids in L. Albert.

### 4.3 Fishing locations of the three main study species

The three main study species were *E. bredoi*, *B. nurse*, and *Lates* (Figure 13). Their fishing areas were distributed at varying depth strata, with a high concentration in the central region. Water depths  $\leq 40\text{m}$  were the main fishing areas for *E. bredoi* and *Lates* (Figure 14, right). Most of the fishing areas were at depths between 1 and 40 m. Fishing locations for *E. bredoi* (green) were highly concentrated in the central region, *B. nurse* (red) in the northern region,

and *Lates spp.* (blue) were equally spread across the whole lake (Figure 14, left). These findings overlap with those of the NASC.

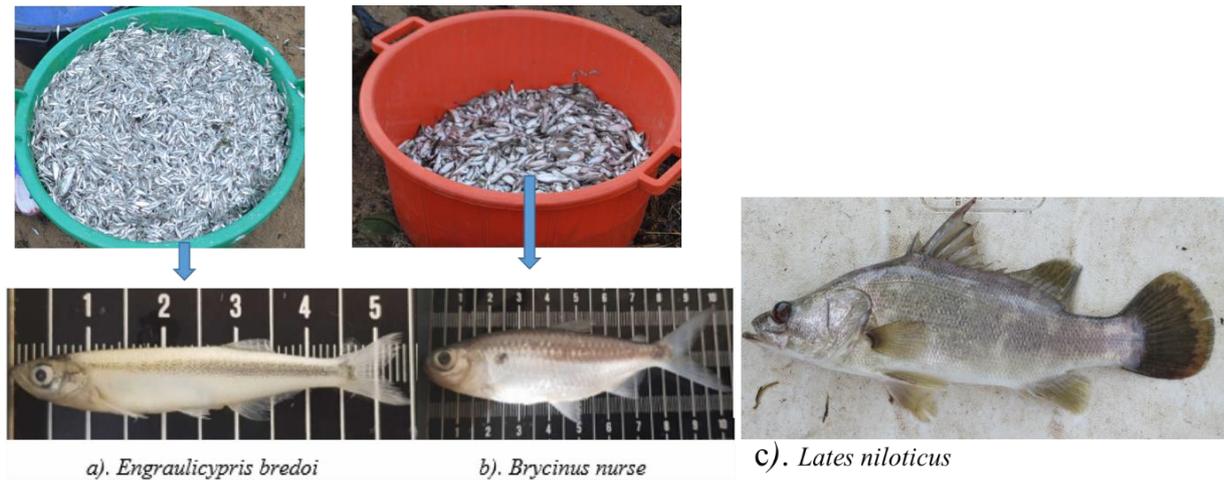


Figure 13. (a and b) Pelagic species, (c) *Lates* exists across the whole lake area (Modified from Nakiyende et al., 2020).

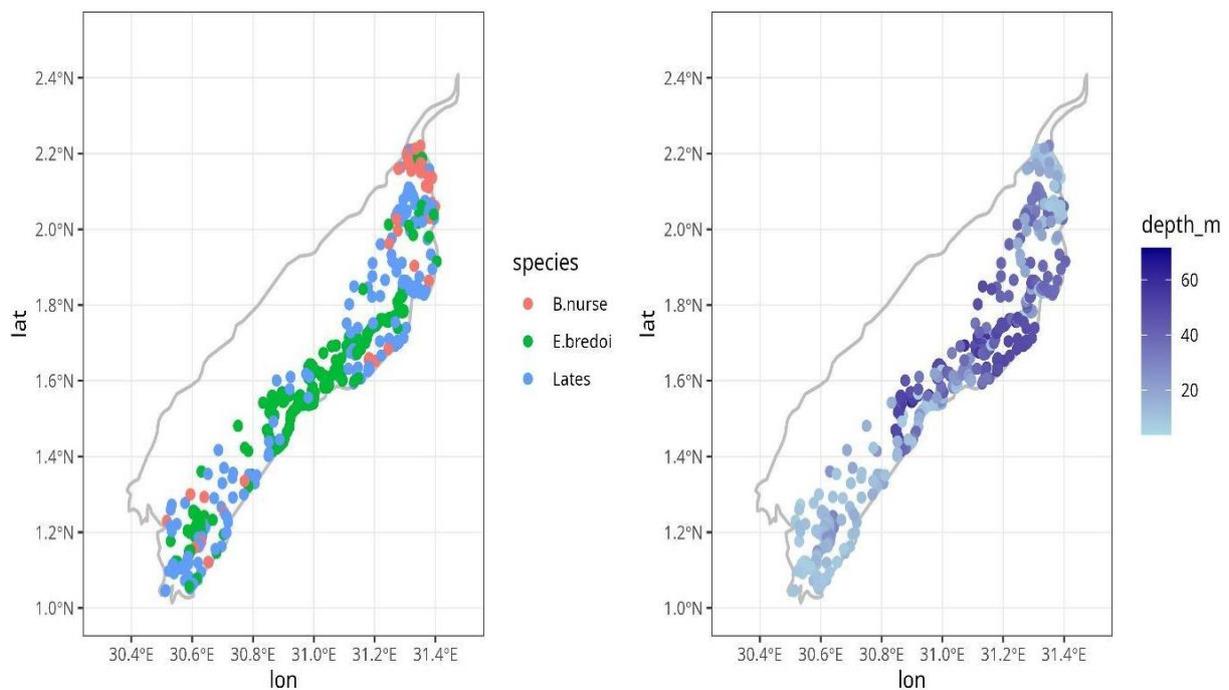


Figure 14. Fishing areas (left) and fishing depths (right) of the three main target fish species in Lake Albert, Uganda. Red points (*B. nurse*), green points (*E. bredoi*), and blue points (*Lates*). Fishing depths (right) dark blue to light blue (deepest to shallowest).

The fishing locations and depth were overlaid with the survey transects during the acoustic survey. The fish landing ports were mapped on the lake shoreline (black dots) (Figure 15).

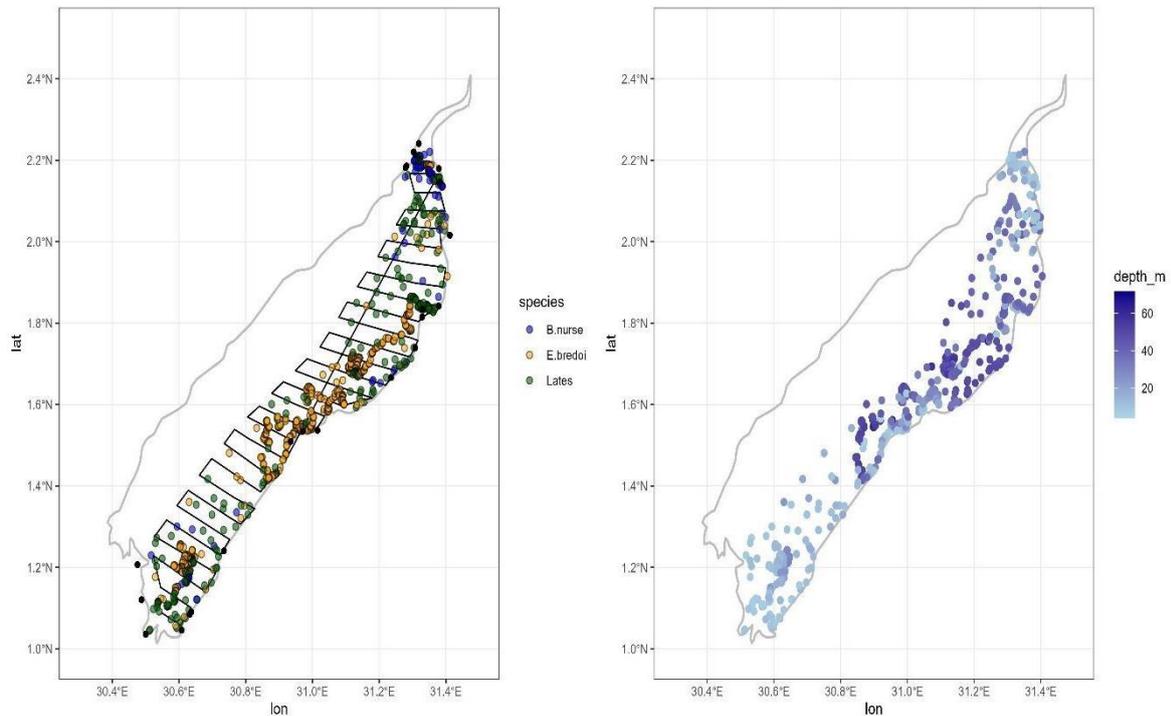


Figure 15. The hydroacoustic cruise track (left) and corresponding fishing depth (right) distribution on L. Albert, Uganda.

Parallel lines: survey transects, fishing locations for *B. nurse* (blue), *E. bredoi* (orange), and *Lates spp.* (green). The black dots are major commercial fishing ports.

#### 4.4 The landing proportions at different landing sites in three regions of L. Albert

Catch proportions were calculated as the percentage of the quantity (%) of all species landed per day at each landing site (site). The landing sites in the northern region were dominated by *B. nurse*, the central region by *E. bredoi*, and the southern region by *Tilapia*. *Lates spp.* was the most common species landed at different landing sites in the three regions (Figure 16, Appendix 5). *E. Bredoi* contributed up to 90% of total catches at Kaiso and Mbegu landing sites in both 2019 and 2020. *B. nurse* dominated the northern region, with approximately 80 % of the total catches at landing sites in this region. The proportion of *Lates spp.* was registered at most landing sites in the range of 20–50% at some landing sites in the northern and central regions. *Tilapia* species dominated the southern region, with the highest proportions of 70 to 80 registered at the Rwangara and Mulango landing sites in 2019 and 2020, respectively, with the Rwangala landing site being the main. The catch proportions in the southern and northern regions were constituted by multiple species (10 species), whereas the central region proportions constituted few (5) species.

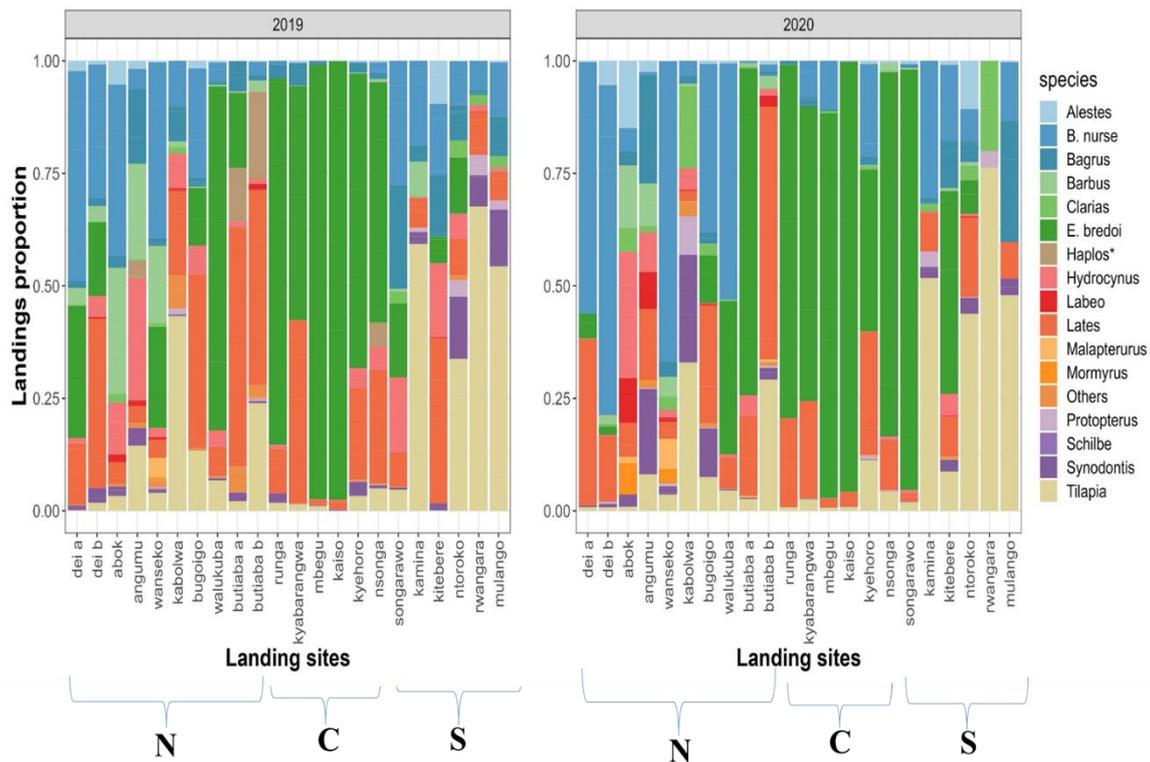


Figure 16. The landing proportions (%) for all landed species in L. Albert in 2019 and 2020 CAS (Data source: NaFIRRI). (N: landing sites in the North, C: landing sites in the central, S: landing sites in the southern region).

Fish landings of the seven major commercial species varied across the three regions of L. Albert (Figure 16). In the central region, *E. bredoi* (80 tonnes) in 2019, in the northern region *B. nurse* (30 tonnes) in 2020, while *Tilapia* dominated the southern region in both 2019 and 2020 (Figure 16). *Lates spp.* was the second most dominant species after *E. bredoi* in the central region and after *B. nurse* in the northern region. The other species targeted in the three regions were *Alestes*, *Bagrus*, and *Hydrocynus* (Figures 17 and 18).

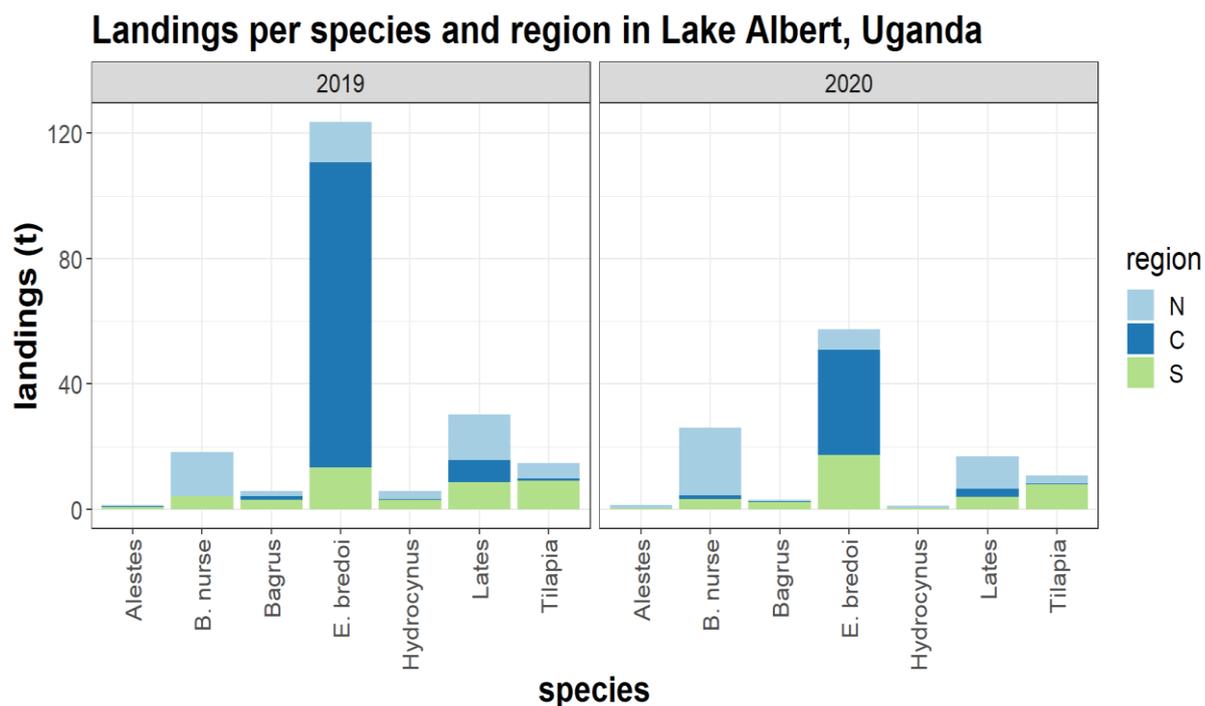


Figure 17. The catch landings of the seven major commercial species of L. Albert in 2019 and 2020 CAS (Data source: NaFIRRI). (N: landing sites in the northern (light blue), C: landing sites in central (dark blue), S: landing sites in southern region (green)).

The size structure of the major commercial fish species landed during November 2020 CAS data was recorded at different major landing sites. The length measurements were as follows: *Alestes spp.* ranged between 10 and 55 cm TL, *Bagrus spp.* between 20 and 90 cm TL, *Hydrocynus forskahlii* between 11 and 57 cm TL, *Lates spp.* between 15 and 125 cm TL, and *Tilapia* between 10 and 50 cm TL (Figure 19).

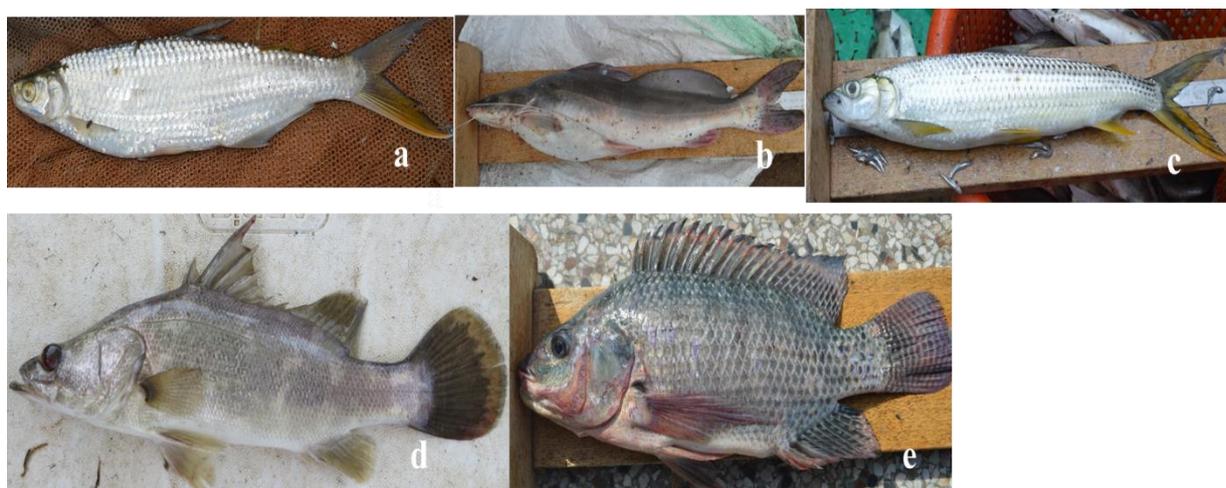


Figure 18. (a) *Alestes baremose*, (b) *Bagrus bajad*, (c) *Hydrocynus forskahlii*, (d) *Lates niloticus*, (e) *Oreochromis niloticus*.

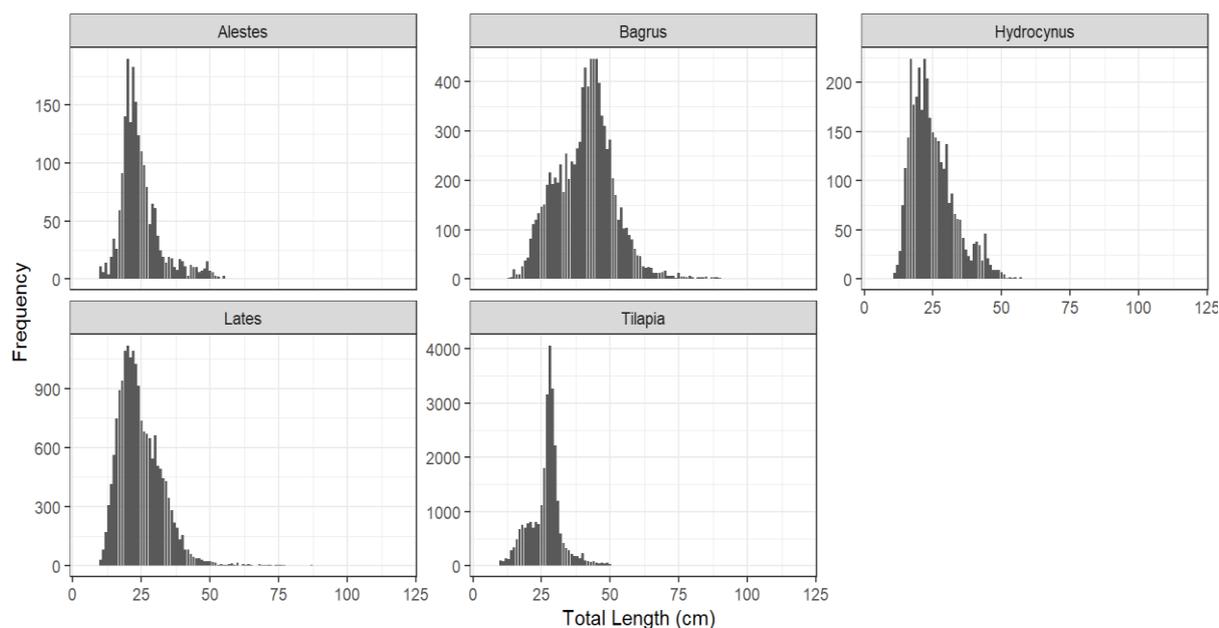


Figure 19. Size distribution (cm) of large-sized targeted species in L. Albert.

The total lengths of *Lates spp.* recorded at different landing sites (clustered into three regions) ranged between 10 and 120 cm (Figure 20). The size distribution of *Lates spp.* was similar in all three regions (northern, central, and southern). However, the Nile perch had two peaks of total lengths of 24 cm and 30 cm.

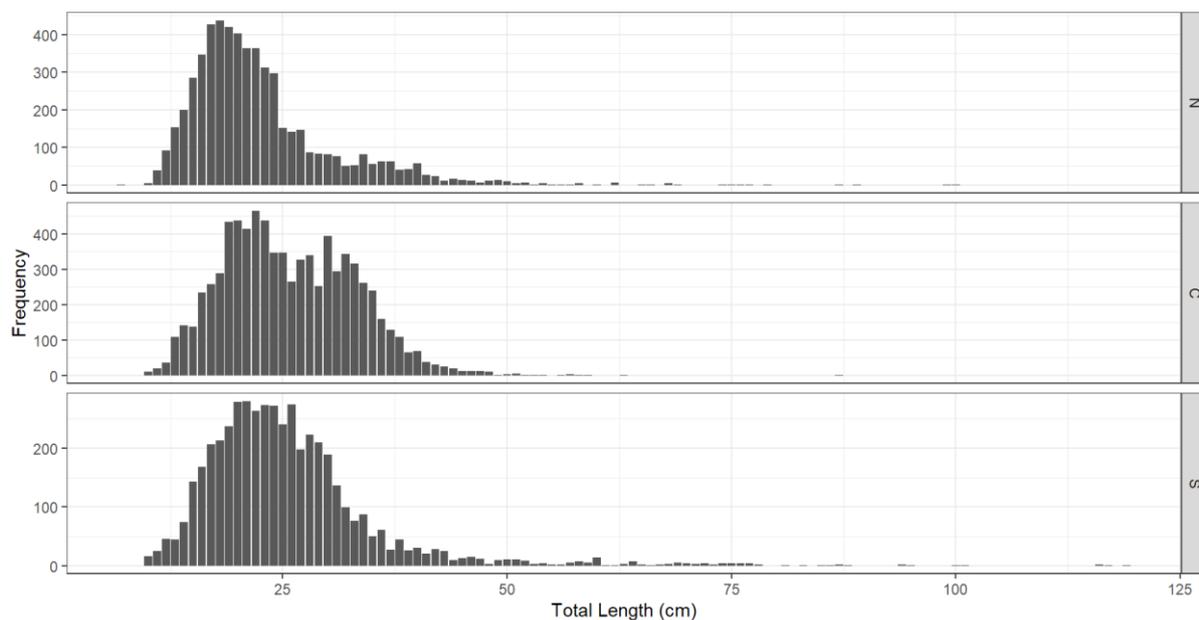


Figure 20. Size distribution (Total length, cm) of *Lates spp* landed in three fishing regions of L. Albert. (N: Northern, C: Central, S: Southern regions).

## 5 DISCUSSION

### 5.1 Environmental water parameters and effect on fish distribution and acoustic sound speed

The variability of environmental water parameters in the three regions and the water depth profile was estimated. The change in environmental water parameters was higher in the top surface water layers of the central region, where temperature, salinity, and dissolved oxygen were compared to deeper water layers. This was attributed to stratified lake conditions, where vertical water mixing was limited. Water stratification is a common phenomenon in great lakes (Guillard et al., 2012), and such conditions are seasonal from September to December. The hydroacoustic survey sampling period was in September, which is one of the months when the lake experiences the greatest stratification. The physical-chemical water parameters of L. Albert were similar to those of previous studies (Nakiyende et al., 2023).

Looking at secchi disc (SD), the low SD was observed in this study around southern and northern regions and can be attributed to the incoming nutrient loads and the influence of inflowing rivers in northern and southern regions. The water transparency of freshwater ecosystems is mainly controlled by the particulate content of inflowing river waters (Talling and Prowse, 2010), which sometimes causes siltation or sedimentation at the lake bottom. The concentration of silts or water solids influences the distribution of fish species and, consequently, the fish acoustic backscatter. The electrical conductivity (EC) estimated in this study ranged from 317.7 to 591.2  $\mu\text{S}/\text{cm}$ , with highest values of 591.2  $\mu\text{S}/\text{cm}$  at most sampled stations. In one of the earlier baseline surveys on environmental water parameters, the EC ranged between 615 and 700  $\mu\text{S}/\text{cm}$  (NaFIRRI, 2007). The estimates in our study were rather low compared to the 720 and 780  $\mu\text{S}/\text{cm}$  that had been reported in the 1960s for L. Albert (Talling, 2009). This is because L. Albert experienced changes in water levels characterised by water overflows and flooding of shorelines in 2021. This could be attributed to the generally lower EC values recorded in this study compared to those in the 1960s. The lowest EC values reported in this study (317.7  $\mu\text{S}/\text{cm}$ ) at some transects in the northern region could be attributed to the water inflow of the Victoria Nile River. The northern region lies within the delta, where ECs as low as 97  $\mu\text{S}/\text{cm}$  have been reported (Talling and Prowse, 2010). In addition, in the southwestern part of the lake, EC values ranged between 619.7 and 636.4 with a mean of 631.7  $\mu\text{S}/\text{cm}$  (Ciwanine et al., 2020). The EC values were higher then, before the long period of flooding in the catchment areas which affected the L. Albert water chemical properties in 2021.

When looking at the pH, the results showed pH ranges 8.0 to 10, which indicated a general moderate alkaline condition of L. Albert that are conducive to physiological and biological activities different L. Albert fish species. This was in a comparable pH range of 7 to 9 that an earlier study reported (NaFIRRI, 2007). Different fish species in L. Albert flourish within pH ranges of between 6.5 to 8 (Sampaio and Freire, 2016). The water pH range between 7.5 and 8.8, with a mean value of 8.0, is suitable alkaline conditions for fish species. Dissolved oxygen levels in the range of 4.0 to 8.2 mg/l were recorded, which falls within the ideal range saturation for freshwater species which exist in L. Albert. The lowest DO levels of 4.0 mg/l recorded around the offshore zone in the northern region were still within limits that can tolerate the physiological activities of some demersal species.

The temperature range of 27.9 to 30  $^{\circ}\text{C}$  from this study is close to the mean of 29.7  $^{\circ}\text{C}$  reported for the DRC portion of the lake (Ciwanine et al., 2020). This temperature range plays a significant role in fish physiological activities and species distribution in different ecological habitats. For example, in Lake Victoria, the spatial and temporal variations in water temperature influence fish distribution, particularly the Nile perch (Taabu-Munyaho et al., 2013). Temperature

changes may cause isothermal or thermal stratification of lake conditions in different seasons which affects fish distribution. This pilot hydroacoustic survey was conducted in September 2021, when most East African water bodies experienced stratification. According to Taabu-Munyaho et al. (2013), a thermocline was reported at temperature ranges 26.3 °C to 26.5 °C and 25.5 °C to 26.5 °C at depths between 25 m and 40 m. The formation of such thermocline water layers affects fish distribution in the following way: water layers hinder fish movement due to limitations in water mixing and oxygen saturation during thermocline conditions (Guillard et al., 2012). The recorded temperature ranges and the season in which the survey was conducted in Lake Albert could be attributed to thermocline conditions.

The salinity results observed during this study could be attributed to tectonic rocks which influence mineralisation and water chemical properties, such as ions (Auge and Nakayi, 2013). Similarly, this lake lies in a semi-arid climatic zone where variations in salinity depend on drought and land patterns around the lake catchment areas (Waiser and Robarts, 2009). However, most inland freshwater lakes have a low salinity of 100 mg/l (Waiser et al., 2009) compared to oceans and seas. The highest salinity ranges observed in the northern (150-300 m/l) were attributed to the influences of the inflowing Victoria Nile River and the highly degraded catchment. The shoreline around this lake region has many ongoing industrial and infrastructural developments related to oil and gas projects around Lake Albert.

#### 5.1.1 Environmental water parameter effect on sound speed and acoustic *backscatters*

The variation in sound speed showed a similar pattern to the changes in water salinity and temperature at different water depth profiles. However, sound speed variability was higher in the surface waters, where water temperature and salinity were higher than in the deeper layers. Sound speed is usually influenced by water temperature, salinity, and water depth (pressure) changes (Bodholt et al., 2002; ICES, 2015). In hydroacoustics, changes in temperature and salinity play critical roles during echosounder calibration and recording fish acoustic energies (Ali et al., 2011). The results in this study showed higher fish acoustic backscatters for the sound speed calculated from environmental water parameters than for the calibrated sound speed. This is because it incorporates water parameter variables at several locations and water depths sampled during hydroacoustic surveys. Although temperature and salinity play an important role in sound speed variations, especially at high frequencies (120 kHz) (MacLennan and Simmonds, 1992), which was used in this acoustic study, such water parameters play a vital role in sound speed in shallow waters (Fraser et al., 2017). In the case of the shallow waters of L. Albert, with a maximum depth of 58 m and an average depth of 25 m, the water depth would not exert high pressure to influence the sound speed. It should be noted that temperature and salinity have spatial and temporal variations; hence, the sound speed varies both horizontally and vertically during acoustic data collection, as observed in this study. This study noted high variations in salinity values recorded at different hydrostations and regions, which will likely affect changes in sound speed and, consequently, the acoustic backscatter. Therefore, continuous adjustment of the sound speed according to salinity and temperature changes should be noted during data collection or while processing data in LSSS or Echoview. The calibration of echosounders should be performed at least one or two times during the hydroacoustic survey at different water depths and environmental water parameters (LVFO, 2018). This would help cross-examine the sound speed variations with backscattered fish intensities. Temperature and salinity influence the sound absorption and attenuation of acoustic energy depending on the acoustic frequency. The reported acoustic scatters were from a split echosounder with a frequency of 120 kHz. Therefore, more echosounder frequencies, such as 38 and 70 kHz, should be used. The 38 Hz frequency is resilient to acoustic sound interference from the environment. Higher frequencies usually experience absorption of acoustic energy (Simmonds and MacLennan, 2005; Fraser et al., 2017). In L. Albert, environmental water parameters,

especially temperature and salinity, vary because it is a rift valley lake at a high altitude and is located on tectonic rocks that influence the chemical properties of water (Nakiyende et al., 2023). The computation of sound speed changes with water parameters and rectifying calibrated sound speed and water parameters would rectify the sound variation with the water profile and survey area for precise acoustic backscattering. The study recommends the use of multiple frequencies and continuous adjustment of sound speed at different water depths and hydrostations for precise acoustic data.

## 5.2 Acoustic backscatter categories and NASC estimates in three regions of L. Albert

As for the fish acoustic backscatters on echograms for L. Albert, the two identified layers at different water depths could be attributed to variations in the environmental water parameters, which influence fish distribution. However, fish distribution can also depend on species habitat and water depth preference due to behavioural and physiological activities. As observed with fish acoustic backscatter comparison between lakes Victoria and Albert, some existing fish schools and single targets were distributed across the vertical water column in L. Victoria but not in L. Albert. The Albert fish acoustic backscatters formed two layers on the echogram, the first layer ranging between water depths of  $\leq 27$  m, while the second layer was  $\geq 37$  m. The two backscatter layers seem to be attributed to fish aggregations influenced by lake stratification (Guillard et al., 2012). In addition, the distribution of different fish and their behavioural characteristics due to diel vertical migration (Proud et al., 2020) are influenced by prey and predator relations. An example species attributed to similar diel vertical migration patterns is the daaga in Lake Victoria (Semyalo et al., 2009); hence, the small pelagics (*E. bredoi* and *B. nurse*) of Lake Albert could likely experience a similar migration pattern over a 24-hour period.

We identified four fish categories (Nile perch, small pelagics, other demersal species, and other species) that were distributed over all regions of Lake Albert. However, the NASC averages for the Nile perch and small pelagics were higher in the deeper waters of the central region. Additionally, Nile perch could be found in both pelagic and demersal water layers, as seen in this study, as in L. Victoria (Taabu-Munyaho et al., 2014), which could partly be explained by the fact that the central region could be the preferred habitat of these species with high NASC averages in deeper waters in the central region. The high acoustic backscatters of Nile perch in deeper waters could be associated with the fact that this species possesses a swim bladder which highly affects the acoustic backscatters of this species. Fish species with swim bladder organ (Lindsey et al., 2010), record high backscatters and this has been fundamental in acoustic studies of different species (Ona, 1999; Simmonds and MacLennan, 2005; Kayanda et al., 2012). The swim bladder organ is responsible for scattering acoustic signals (90-95%); therefore, high backscatter intensities are due to backscattered energies from species such as Nile perch. The inshore transects in the northern region had high acoustic fish backscatters, which were overlapping and indistinguishable for classifying fish into categories. One of the reasons for this is that fish species aggregations were in-depth profile between 8 to 15 m, and the waters around these transects are breeding and nursery areas of many fish species (such as Nile perch, *Bagrus* species, and *Tilapias*) and are enriched with nutrients (NELSAP-CU, 2019). In addition, the ecological area with food nutrients from inflowing Nile waters and conducive water parameter ranges influence fish distribution. However, trawl surveys alongside hydroacoustic surveys in such areas are recommended to assess fish species composition and biological characteristics.

The NASC averages for other demersal and other species were lower than those for Nile perch and small pelagic NASC averages. The difference in NASC averages estimated in different

regions and for each fish acoustic backscatter category could be explained by the multispecies nature of the L. Albert system, in which different fish species are widely distributed and prefer a variety of habitats and water depth profiles (Taabu-Munyaho et al., 2014). These two categories were recorded around transects with water depths of  $\geq 40$  m, while other species were noted around inshore and shallow waters ( $\leq 20$  m). However, this study was limited to a hydroacoustic survey, but combining it with a trawl survey would capture the fish species composition in more detail as well as make it possible to estimate fish densities and biomass for each fish category.

However, acoustic fish backscatter is influenced by many other factors, such as the physical-chemical properties of water, as shown in this study. Therefore, future studies should compare spatial and temporal changes in water parameters and fish distributions. In nature, water particles and fish distributions are not homogenous, from suspended particles to fish distribution from the water surface to the bottom, and consequently, the distribution of the acoustic backscattering coefficient (MacLennan and Simmonds, 1992; Korneliussen et al., 2009). The distribution and morphological characteristics of some fish species (small pelagics) influence NASC values (Simmonds and MacLennan, 2005). Some species exhibit aggregation patterns, while others exhibit schooling patterns, which change over a 24-hour period. The Daaga species in L. Victoria, for example, share morphological characteristics similar to those of Muziri and Ragooge in L. Albert. Small pelagic species exhibit schooling behaviour and diel vertical migration patterns; therefore, they can be found at different water depths depending on the time of day. This behaviour affects the acoustic backscatter and estimated fish densities in the water column (Proud et al., 2020). Similar cases of high backscatter intensities were observed in the central and northern regions, in which the NASC averages for the categories (Nile perch and small pelagics) had high backscatters from schooling fish and fish aggregations. However, this study was limited to trawl sampling, which could have provided a more detailed fish species composition around such locations. With the use of -72 dB, the acoustic scatters from small aquatic organisms, such as zooplankton, were removed. However, zooplankton and fish biology would further explain the results on fish aggregations or high acoustic fish scatters in the central and northern regions. The L. Albert ecosystem is enriched with abundant zooplankton communities (Lehman et al., 1998). Zooplankton such as phemeropterans, Odonata, and chironomids are abundant, and some species, such as freshwater shrimp (*Caridina nilotica*), affect the scattered acoustic intensities. Freshwater shrimp contribute to the food trophics of lakes Albert and Victoria as they are important prey for small pelagics and juvenile Nile perch (Ngupula and Mlaponi, 2010). Different fish species and sizes, zooplankton presence, and behavioural characteristics influence acoustic scattering properties. Hydroacoustic surveys with two or more frequencies aid in distinguishing the acoustic signals. Hence, areas with high NASC estimates require further investigation in future hydroacoustic sampling.

### 5.3 Fish landings and fishing areas of three major study species

The L. Albert aquatic ecosystem supports diverse biotic and abiotic factors that influence ecosystem functioning and fisheries activities (Nakiyende et al., 2023). The landing results estimated 17 commercial species distributed among different landing sites in the three regions of L. Albert. The seven major commercial species recorded are *A. baremose*, *Bagrus spp*, *H. forskahlii*, Tilapias, *Lates spp*, *B. nurse* and *E. bredoi* and among these, three (*Lates spp*, *B. nurse* and *E. bredoi*) the target study species which were dominant at most landing sites of L. Albert. The total annual catches of 17 fish species were 335,474 t and 348,535 t in 2019 and 2020, respectively (NELSAP-CU, 2021). Our landing results showed that these three major species contributed to more than 80% of the total landings. The commercial species and

landings at different landing sites imply fish species abundance and distribution in different areas. The proportions of fish species landed each day of fishing are related to the species abundance in the fishing areas and regions which we explained with the NASC value in different regions. The relationship between catch rates and catch proportions (Haggarty and King, 2006) explains the relative abundance of species. The available species in a fishery are assessed by habitat distribution, which is correlated with the species catch composition. Although there are still limitations to fisheries data and information in L. Albert, this study shows that fishery-dependent surveys should be implemented in addition to improved hydroacoustic surveys.

The three study species dominated the landings, and their proportions in the northern, central, and southern regions can be explained by the high total annual commercial catch and revenue (NELSAP-CU, 2021). The estimated 121,106 t of *E. bredoi*, for example, was valued at US\$ 32,084 (Natugonza and Musinguzi, 2022), and the two small pelagic species contributed over 70 % of the total annual catch landed on Lake Albert (NELSAP-CU, 2021; Nakiyende et al., 2022). Our results showed a similar pattern, with small pelagic species registering the highest landing proportions at landing sites in the central and northern regions, whereas *Lates spp.* registered moderate landing proportions across the three lake regions. The two small pelagic species are endemic to L. Albert (Greenwood, 1976) and form part of an important fishery that supports people's livelihoods. Nevertheless, information on the biology and ecology of small pelagic fish remains limited. However, it has been reported that *B. nurse* grows to a maximum size of 25 cm FL and a body weight of 200 g, whereas *E. bredoi* rarely exceeds 4.5 cm Standard Length (SL) and a body weight of < 3 g (Greenwood, 1976; Froese and Pauly, 2023). The NASC averages for both Nile perch and small pelagics were high in the central region which correlates with the high landing proportions in the same region. The central region inshore waters are dominated by *E. bredoi*, while offshore deep waters are concentrated by Nile perch. Similar studies during peak fishing seasons on moonless nights reported high concentrations of fishing boats and gear of *E. bredoi* in the shallow and pelagic layers of the central region (Nakiyende et al., 2022). The results of high NASC averages and landing proportions showed a similar pattern of species dominance and concentration in the central and northern regions of L. Albert.

For Nile perch, the acoustics, landings, and fishing locations showed high concentrations of species in the central region. In L. Albert, there are two species under the Latidae family, *Lates niloticus* and *Lates macrophthalmus* (Greenwood, 1976). Our results aggregated these two species into *Lates spp.* because we were limited to classifying them at the species level in the absence of catch estimates. However, enumerators at landing sites could hardly classify the two species. *Lates niloticus* is the most valuable species in Lakes Albert and Victoria, with total annual catches of 31,258 t and 61,744 t, respectively (NELSAP-CU, 2020; LVFO, 2021). The species is the most commercially valuable species and therefore needs appropriate management and exploitation guidelines in Lake Albert. *Lates spp.* inhabit both pelagic and demersal layers. The Nile perch NASC estimates in our study were highly concentrated in the deeper waters of the central region. However, the water depth profiles of 4–10 m showed the highest NASC values. This could be explained by diel vertical migration, which is experienced by most small pelagics during feeding. In addition, Nile perch feed during the daytime and can be pelagic or demersal (Taabu et al., 2014). The hydroacoustic survey was conducted during the daytime. Nile perch reportedly grow to a maximum length of approximately 2 m TL and a weight of more than 200 kg (Ogutu-Ohwayo, 1988; Ogutu-Ohwayo and Balirwa, 2006; Njiru et al., 2018). Studies on L. Victoria have shown that this species is widely distributed across the entire water column, where it actively preys on other species (Goudswaard et al., 2004; Taabu-Munyaho et al., 2014). Some transects and regions, especially the northern region and inshore

transects, were difficult to distinguish high backscatters of species. High backscatter and large individuals in such regions should be assessed in future trawling and hydroacoustic surveys. Hence, hydroacoustic studies can be complex in a multi-species fishery such as L. Albert, and the study focus and designs should aim at key commercial or species of interest at the time.

#### 5.4 Hypotheses findings

(i) There was a statistically significant difference in the sound speed between the regions and zones of L. Albert. The NASC averages of the four species categories changed with depth intervals. Hence, environmental parameters affect fish distribution and acoustic sound speed in different lake conditions and areas.

(ii) Fish landings consisted of 17 different fish species landed at different landing sites distributed across the three regions of Lake Albert. However, the highest proportions were composed of four major species: *E. bredoi* (90%) in the central region, *B. nurse* (75%) in the northern region, and Tilapia (80%) in the southern region. However, Nile perch contributed to 25 -50% of all fish landing sites in the entire lake area. By mapping the NASC averages of some of these species, their distribution and preferred habitats of high concentrations were mapped.

#### 5.5 Conclusions

1. It was observed that water environmental parameters varied in different regions and water depths. Thus, the study reported the sound speed changes with water parameters across the lake profile and consequently underestimated the NASC values if acoustic data did not consider in-situ sound speed. The sound speed should always be assessed and adjusted per transect in case there is variation either during the acoustic survey or during data processing in LSSS or Echoview.
2. There is a need to sample physical-chemical parameters at many hydrostations during acoustic data collection in different seasons when L. Albert is stratified and mixed in different seasons. However, acoustic backscattering coefficients can be affected by other factors, such as water-suspended solids and lake bottoms.
3. This is the first hydroacoustic survey to establish baseline information and protocols for three dominant species (*Lates*, *E. bredoi*, and *B. nurse*). L. Albert being a multi-species fishery system, the four fish backscatter categories i.e., Nile perch, small pelagics, other demersal species and other species NASC averages were estimated and mapped for entire lake.
4. Hydroacoustics, along with information on species biology and the ecological characteristics of Nile perch, were based on previous studies in L. Victoria. Four acoustic backscatter categories were identified to enable data processing in the LSSS. The NASC distribution for the four fish categories was averaged in box grids. Two layers of backscatter intensities were observed in some regions, especially between 4 to 27m and  $\geq 38$ m water depth profiles. The study reported the backscatter as densities in terms of NASC ( $m^2/nmi^2$ ) distribution in 4 nm by 4 nm box grids.
5. The reported NASC values in some areas would require future studies through trawling and hydroacoustic surveys to verify the species acoustic characteristics and environmental parameters at such stations. The schooling behaviour of some fish species affects the high

scattering coefficients and reported fish densities. There are still limitations in the information on species size structures, abundance and distribution, fish stock biomass, and spatial and temporal variations. Combined trawling and hydroacoustic surveys would provide precise data and information for further stock assessment studies and ecosystem-based fisheries management, which would help safeguard local livelihoods.

## 5.6 Recommendations

1. Correcting the acoustic backscatter using the in-situ sound speed from environmental water parameters, as the sound speed changes according to water parameters (salinity and temperature) at different water depths and regions.
2. Enhancing hydroacoustic surveys by developing additional trawls to estimate fish species composition, density, and biomass.
3. Conducting fish target strength experiments to estimate TS length relationships, which are needed to convert the backscatter coefficient to biomass. TS *in-situ* experiments alongside modelling TS for major species to develop acoustic information to guide further studies on Nile perch, Ragoogi, and Muziri of L. Albert.
4. Future hydroacoustic surveys should use two or more echosounder frequencies (70, 120, and 200 kHz) to distinguish acoustic signals from different aquatic organisms, such as zooplankton and fish.
5. An ecosystem-based fisheries management approach should be established through periodic fish stock monitoring and scientific information to guide holistic studies.

During this hydroacoustic study, the results and skills acquired will be important in the future to affect the following lessons learned on hydroacoustics and L. Albert fisheries:

- a) Data processing using the LSSS software instead of Echoview should be implemented, which has an advanced graphical user interface, acoustic data processing features, and an LSSS database with taxonomic names for most species and their families.
- b) The acoustic sound speed is affected by environmental water parameters such as temperature, salinity, and pressure. Hence, the sound speed must be calculated and rectified during data collection or data processing to ensure the correct estimation of NASC values.
- c) Fishing experiments and target fishing should be conducted to verify the acoustic signals of species and fish schools or aggregations in certain regions.
- d) Periodic acoustic surveys and random transect sampling over time will provide appropriate estimates of fish density and biomass.
- e) Hydroacoustic data should be collected in different seasons to establish temporal and spatial data and information for different lake conditions. That is, mixed and stratified lake conditions.

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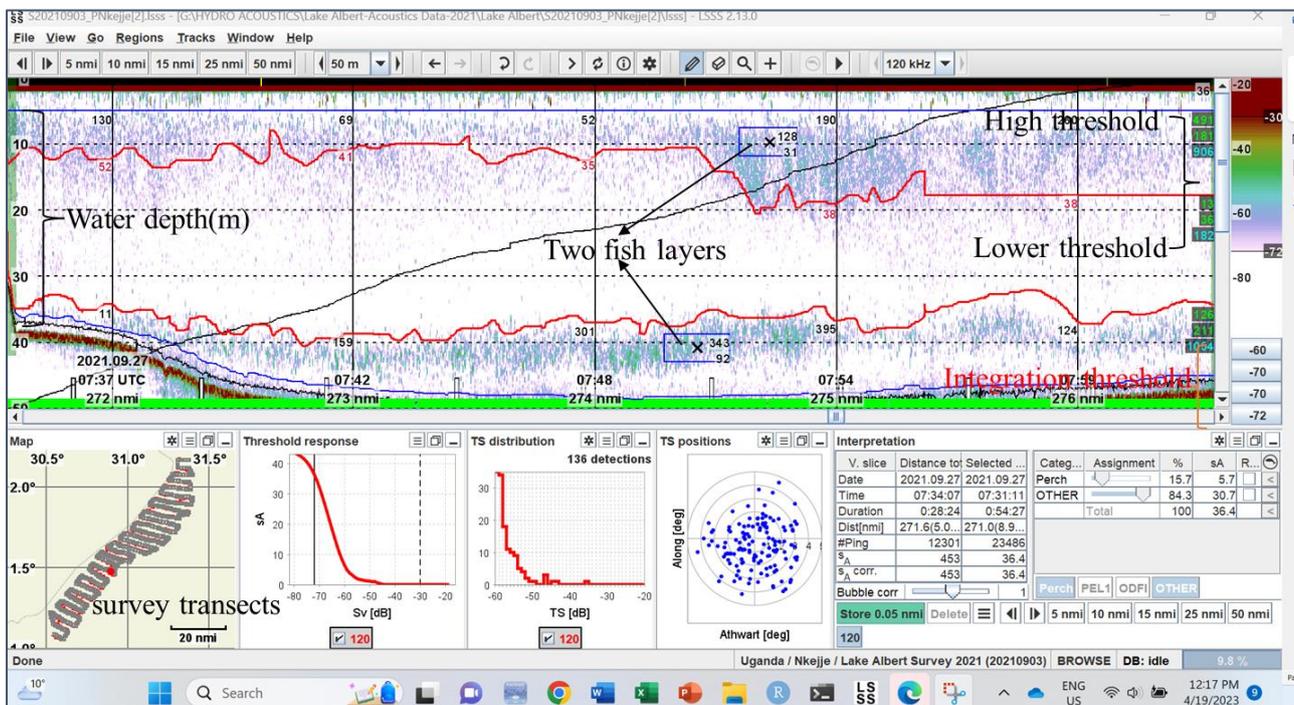
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**APPENDICES**

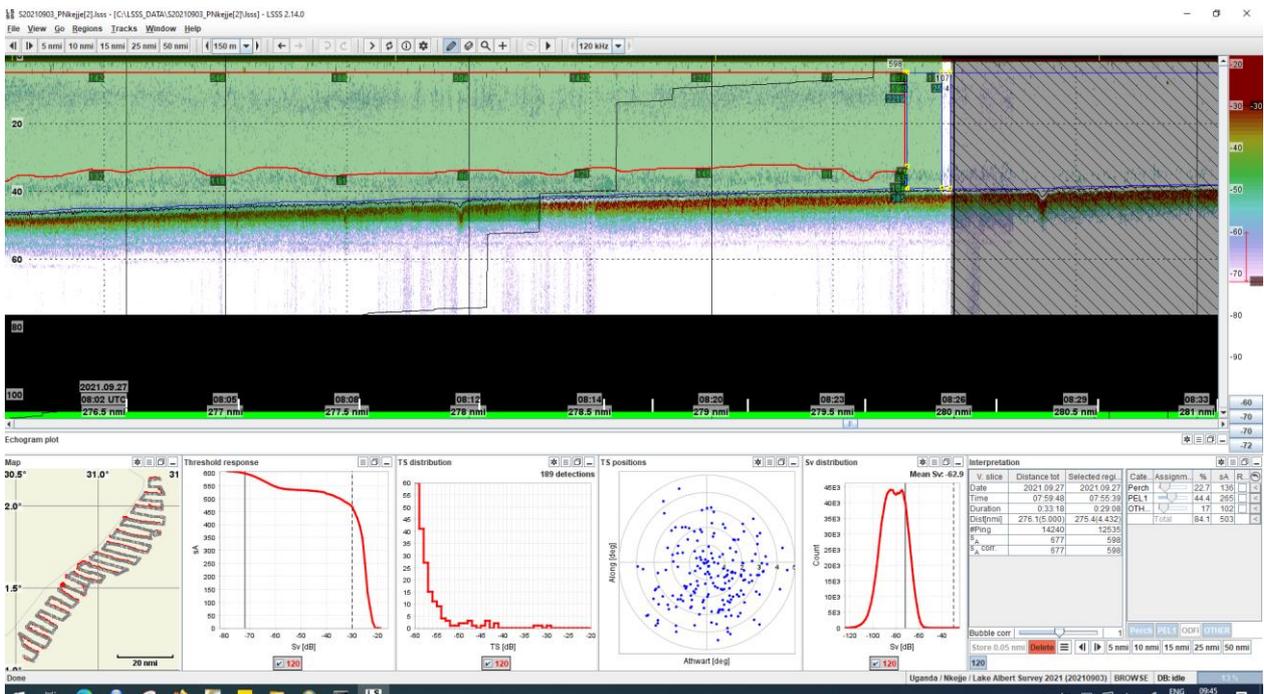
Appendix 1. Average summaries for sound speed, salinity, and temperature

Region	Zone	Sound speed(m/s)	Salinity(mg/l)	Temperature (°C)
N	I	1503.6029	294.0	27.5
N	O	1503.6951	306.9	27.5
C	I	1504.7834	319.6	28.0
C	O	1504.1897	319.8	27.7
S	I	1503.9872	321.2	27.6
S	O	1503.6490	321.9	27.5

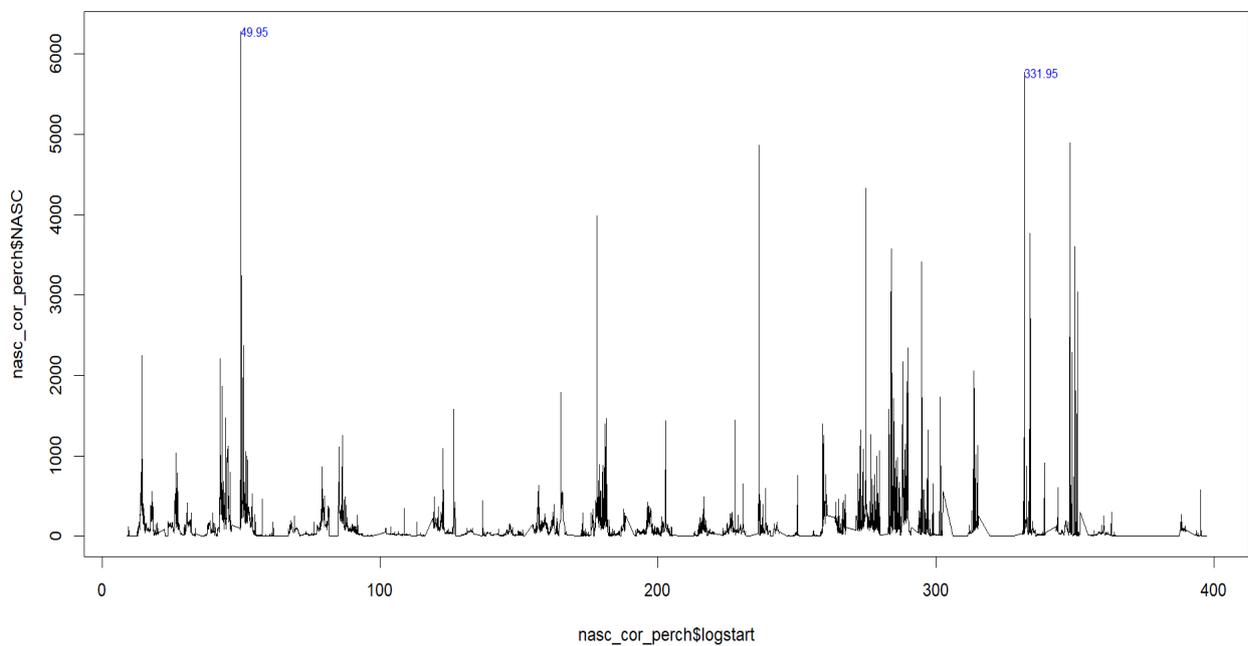
Appendix 2. Graphical User Interface (GUI) for interpreting backscatter data in LSSS and fish categories of L. Albert in September 2021 survey.



Appendix 3. The acoustic backscatter categories and regions of bad exclusions.



Appendix 4. The highest Nile perch NASC values were recorded at 49.95 nm and 331.96 nm.



Appendix 5. Fish species proportions (%) per day at major landing sites of L. Albert.

