Exploring Nitrogen Cycling in Lagos Lagoon, Nigeria: First Steps Towards an Integrated Monitoring Program

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Submitted in partial fulfilment of the requirements
for the degree of Master of Sciences

at

Dalhousie University Nova Scotia, Canada
October 2024

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Abstract

Lagos lagoon, a vital coastal ecosystem in West Africa, sustains the livelihoods of millions of people amidst escalating pollution threats stemming from dense human habitation in its watersheds. Despite facing severe degradation and diminished ecosystem services, the lagoon lacks a coordinated water quality monitoring program. Establishing such a program requires an integrated measurement of nutrient levels within the lagoon in time and space that could serve as baseline to inform future monitoring efforts. Previous measurements in Lagos lagoon have been performed sporadically and have been faced with various challenges which have hindered the accuracy and reliability of measurement efforts.

In Chapter 2 of this study, we employed stable isotope analyses of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) in representative taxa (mangrove leaves, invertebrates, and fish) and sediment to give an integrated view of spatial and seasonal variabilities of nutrient sources and trophic dynamics. The $\delta^{13}C$ of sediments and biota was generally lower (< -25 ‰) in the more freshwater influenced northern and eastern zones of the lagoon, and higher (> -25 ‰) in the more marine influenced western and southern zones. The observed distribution of $\delta^{13}C$ was therefore attributed to relative differences in terrestrial vs. marine sources of carbon. The $\delta^{15}N$ of sediments and biota was most strongly impacted by trophic effects and increased predictably with known or inferred trophic position. Compared to spatial and trophic effects, seasonality had relatively minor and inconsistent effects on $\delta^{13}C$ and $\delta^{15}N$. Calculated baseline $\delta^{15}N$ averaged 5.2 ± 2.6 ‰ for the northern, eastern and western zones and was lower (1.6 ± 1.3 ‰) in the southern zone. The baseline $\delta^{15}N$ values were all within range of natural seawater nitrate and terrestrial soils nitrate, which made it difficult to attribute specific anthropogenic effects on nitrogen cycling in the lagoon. Overall, these data may serve as an important temporal baseline for future monitoring in Lagos lagoon. Going forward, targeted analysis of select bioindicator taxa over wider ranges in space and time is recommended.

In Chapter 3, a pilot study to compare nutrient analyses results between a laboratory in Canada and one in Nigeria is described. This aimed to take a preliminary step toward understanding nutrient measurement practices in the lagoon and identify and overcome the challenges facing them. The pilot study also aimed to determine the feasibility of such international collaboration in environmental research and to highlight some challenges. We found similarities in patterns but significant differences in nutrient levels, with the Unilag laboratory recording lower levels than the CERC-Ocean laboratory. On the other hand, there was good agreement in the analyses of reference samples. We suspect that different steps in sample analysis, problems in data workup, and reporting might be sources of these discrepancies. Challenges encountered during the study are described and recommendations for improvement are suggested.

The findings from this preliminary comparison of nutrient analysis provide the first step toward resolving discrepancies in nutrient level measurements in Lagos lagoon and improving accuracy and reliability. The data from this thesis may serve as a baseline for future monitoring and assessments in the lagoon. They can also be built upon to facilitate the establishment of a future monitoring program for the lagoon.

List of Abbreviations Used

ANOVA…….....Analysis of Variance
AP……...……... Apapa
CERC-Ocean……...… Canada Excellence Research Chair in Ocean Science and Technology
CRM…… Certified Reference Material
DIC……...…… Dissolved Inorganic Carbon
DIN…… Dissolved Inorganic Nitrogen
DOC……...…… Dissolved Organic Carbon
EP…… Epe
HC ……Herbivorous Consumer
IK……...……Ikorodu
IRMS……...……...…….. Isotope Ratio Mass Spectrometer
NIOMR...……...…….. Nigerian Institute for Oceanography and Marine Research
OC ……... Omnivorous Consumer
OSM…….…….. Ocean Science Meeting
PAT…….……. Potassium Antimonyl Tartarate
PC ……..... Piscivorous Consumer
PP ……..Primary Producer
RMNS……Reference Material for Nutrients in Seawater
SFCA-PF…….. Surfactant-Free Cellulose Acetate with Prefilter
TP……Trophic Position
Unilag…… University of Lagos
VGC ……Victoria Garden City
VPDB……...……Vienna PeeDee Belemnite

Acknowledgments

First and foremost, I express my gratitude to God Almighty for His guidance and blessings throughout this journey. I am deeply grateful to the many wonderful people whose support and encouragement made this thesis possible. My heartfelt thanks go to my supervisors, Dr. Owen Sherwood and Dr. Douglas W.R. Wallace, for their invaluable guidance and patience. It was a pleasure working with you. My thanks also go Vittorio Maselli for the for valuable advice as my thesis committee member. I also extend my gratitude to Dr. Juliet Igbo, the members of NIOMR, Dr. Akeem Abayomi and the Biochemistry laboratory at the University of Lagos. Your support in planning, fieldwork, and laboratory analyses was crucial to this project's success. Special thanks to Dr. Simone Le Gendre and the DOTCAN team for your encouragement and supports. I appreciate the CERC-Ocean and Stable Isotope Biogeochemistry laboratories at Dalhousie University for welcoming me. Special thanks to Claire, Natasha, Wilder Greenman, Ali, Ricardo, Nina, Shaomin, Kitty, and Wills for their guidance and support throughout my journey in graduate school.

Finally, I am forever grateful to my family—my parents, sisters Dr. Rita Orji and Dr. Fidelia Orji, and my brother Mr. Able Orji—for their unwavering support, encouragement, and prayers. Thank you to all friends who contributed to the success of this graduate program. This incredible journey would not have been possible without your support and guidance.

Chapter 1

Introduction

1.1 Background

Coastal lagoons are among the most ecologically important coastal ecosystems in the world and play an important role in supporting human well-being. They occupy about 13% of the area of the world's coastlines (Kjerfve, 1994), serving as transitional ecosystems connecting land and sea. They rank among the marine habitats with the highest biological productivity (Alongi et al., 1998; Kennish & Paerl, 2010) and provide habitat for diverse organisms, providing shelter for valuable biodiversity (Grillo & Venora, 2012). They are characterized as being shallow with strong lateral physical-chemical gradients (Solidoro et al., 2010; Pérez-Ruzafa et al., 2011).

Lagos lagoon, with an area of 6400 km2 is located in southwestern Nigeria in the Gulf of Guinea. It provides diverse and important ecosystem services including sources of food, irrigation water, recreation and means of transportation (Pérez-Ruzafa et al., 2019; Velasco et al., 2018) to the population inhabiting the watersheds in and around the city of Lagos. The lagoon is a major source of livelihoods to Lagos city, one of the most densely populated cities in the world with about 22 million inhabitants (Ezeudu et al., 2021). The lagoon is also used as a sink for anthropogenic waste including agricultural, industrial, and human waste which are mostly untreated (Ajao, 1996).

The ability of Lagos lagoon to provide these ecosystem services is increasingly threatened by pollution. The activities of the burgeoning human population and lack of proper waste management are increasing pollution load on the lagoon. Activities such as domestic upkeep (hand laundry, effluent, greywater), agricultural land use of the catchment areas, and urbanization introduce large volumes of pollutants into the lagoon annually (Clarke et al., 2020; Nkwoji et al.,

2020; Nwankwo, 2004). Sewage has been recognized to cause significant threat to marine ecosystems, detrimentally affecting water quality, leading to destruction of aquatic lives and posing health risks to humans (Dutto et al., 2012).

Over the last few decades, the human population, and the number of industries within Lagos city and around the lagoon have grown rapidly and are still growing at an increasing rate. The increase in population is accompanied by increases in sewage generation. Large fluxes of sewage coupled with inadequate treatment and proper disposal systems results in the direct and indirect discharge of untreated sewage and effluents from homes and workplaces into the lagoon (Awomeso et al., 2010; Longe & Ogundipe, 2010). There has also been increased fertilizer usage for agriculture and growing industrial effluent generation. These issues pose a threat to the health of the lagoon ecosystem.

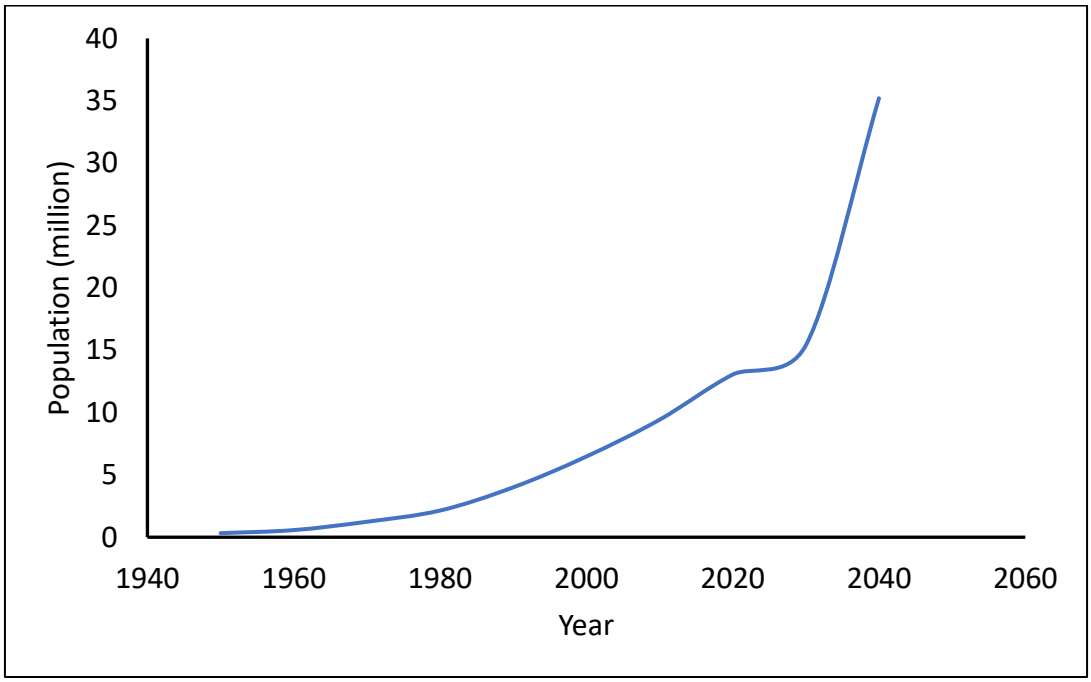


***Figure 1.1**: Growth in Lagos population by years (United Nations, 2018).*

Contaminants from sewage and other effluents containing nitrogen (N) and carbon (C) pose serious threats to local ecological stability. Increased N loading causes eutrophication which leads to algal blooms, low oxygen (hypoxia), death of fish and seagrass, and reduction in essential lagoon habitats (Rabalais et al., 2014). While the extent of sewage contamination may be hard to track based on C or N concentrations alone, stable isotopes of ^{15}N and ^{13}C may provide time-integrated tracers of sewage contamination (Costanzo et al., 2001; Fry, 2006; Risk et al., 2009).

Several previous studies have highlighted an urgent need to address the unhealthy state of the Lagos lagoon (Adesalu et al., 2010; Ajao 1996; Akagha et al. 2020; Obi et al. 2016; Nkwoji and Awodeyi 2018; Nkwoji et al., 2010; Nkwoji et al., 2020; Oladosu et al. 2017; Olayinka et al. 2016; Onyema 2007; Oyatola et al. 2021; Yakub et al. 2011). Over the decades, these studies have attempted to measure and report the level of some pollutants in Lagos lagoon and identify their sources (Adesalu et al., 2010; Nkwoji & Awodeyi 2018); however, most of these measurements are based on instantaneous sampling that was scattered in space and time (Fig. 1.2). A systematic, integrated, and coordinated sampling and measurement approach is required for the planning and establishment of an effective management program. In this study, I aim to use stable isotopes to produce the first integrated measurement and characterization of pollution in the lagoon.

The lack of prior systematic and integrated measurement motivated the second chapter of my thesis, which reports on an exploratory investigation of the stable isotope ecology of the Lagos lagoon. This initial exploratory study of ^{13}C and ^{15}N stable isotope distributions was intended to provide baseline data about pollution levels and a basis on which to plan further work. Ideally, the baseline would be established from an extensive program of time- and space- resolved sampling and analyses throughout the lagoon, that could be repeated, as well as monitoring of inputs from

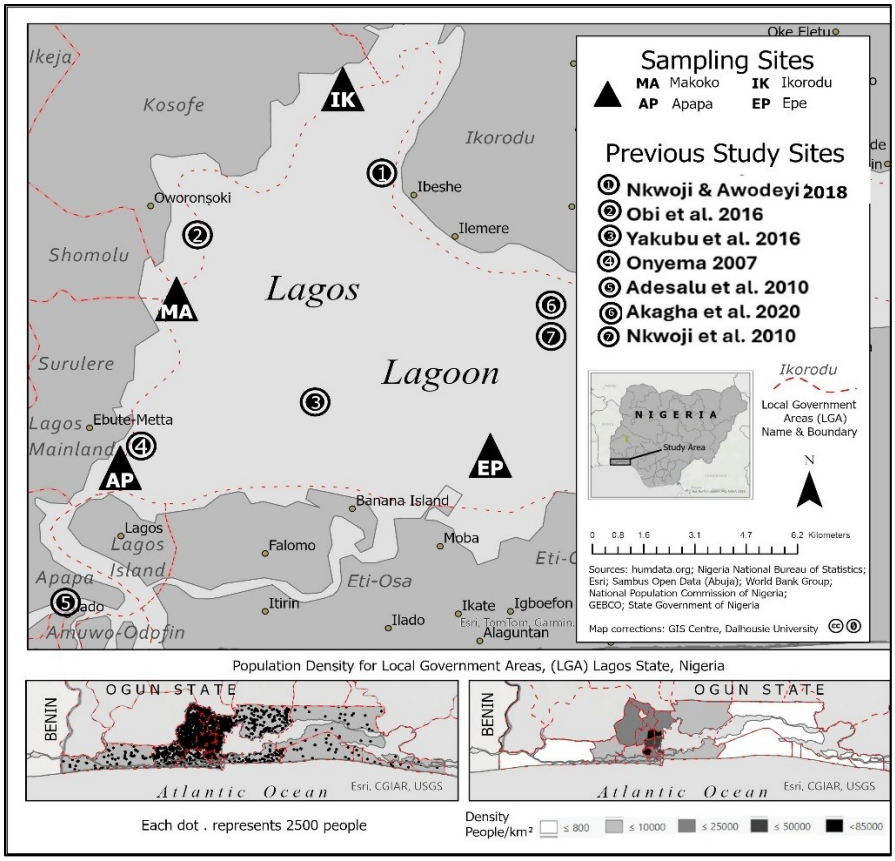


Figure 1.2 *Map of Lagos lagoon highlighting selected areas sampled by previous studies and our current sampling sites as shown in the Chapter 2.*

key discharge points. These may require reoccurring resources which is not within reach at the present time, but a future research effort of this type could build off my initial work.

The planning and establishment of a long-term monitoring program is therefore a desired outcome of this study. Such a program would require regular sample collection and analyses. However, such a monitoring program cannot rely on analyses by foreign labs as this initial study does. Ultimately, effective and sustainable monitoring must be operated in Nigeria by local institutes or agencies. In response to these challenges, a collaborative effort that starts to address measurement methods and data quality control was initiated between Dalhousie University and our partnering institution, the University of Lagos. Chapter 3 of this thesis discusses an initial intercomparison of

nutrient analyses conducted as part of this collaborative effort, highlighting some of the challenges encountered during the exploratory program, and provides recommendations for next steps and future initiatives.

1.1.1 Stable isotope measurement

Stable isotope analyses of C and N provide an effective proxy for studying trophic ecology in coastal environments including lagoons (Nixon et al., 2007; Oczkowski et al., 2008; Risk, et al., 2009). They have been used as tracers for tracing of the wastewater inputs on aquatic receiving environments (Fraser et al., 2024; Sánchez et al., 2020; Savage, 2005). Isotopes of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) are the two isotopes frequently measured in ecological studies because of their ability to be used as a tracer (Fry, 2006). Each have two naturally occurring stable isotopes (^{12}C, ^{13}C and ^{14}N, ^{15}N; Fry, 2006).

Stable isotope ratios are reported in delta (δ) notation according to the following equation (Eq. (1)):

$$\delta X‰ = [R_{sample} / R_{standard} - 1] \times 1000 \quad (1)$$

where X represents the heavier isotope, R_{sample} denotes the ratio of the heavy isotope to the light isotope within the sample being analyzed, and $R_{standard}$ represents the ratio of the heavy isotope to the light isotope within the standard. For carbon isotopes, the standard is Vienna Pee Dee Belemnite; for nitrogen, it is the N_2 in air. An increase in the δ value indicates a greater abundance of the heavier isotope relative to the lighter isotope, termed enrichment (Fry, 2006). Conversely, lower δ values indicate a reduced abundance of the heavier isotope relative to the lighter isotope, termed depletion.

1.1.2 The role of stable isotopes of carbon and nitrogen in identifying sources, distribution, and impacts of pollution in aquatic ecosystems

Stable isotopes of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) have proven useful for studying eutrophication processes in aquatic ecosystems. They can be used as tracers to investigate sources, including anthropogenic inputs, as well as cycling and transformation of nitrogen and carbon in aquatic environments (Li et al., 2006; Costanzo et al., 2001; Vander Zanden et al., 2005), and impacts on food webs (Fraser et al., 2024; Mazumder et al., 2015). Different nutrient sources to lagoon ecosystems, such as terrestrial versus marine organic matter, differ in their $\delta^{13}C$ values (Post, 2002). This makes it possible to track, quantify and distinguish different sources of energy. For example, $\delta^{13}C$ has been used to track terrestrial carbon sources (Fraser et al., 2024), because terrestrial $\delta^{13}C$ signature are usually lighter ($\delta^{13}C$ ~ -28‰) than those in marine carbon pools (> ~22‰; Fry, 2006; Post, 2002).

The $\delta^{15}N$ value of tissue samples can also be used to track specific sources of nutrients supporting the base of the food web (Zanden & Rasmussen, 2001). This is because isotopic fractionation causes different sources of N to differ in their $\delta^{15}N$ signatures (Heaton, 1986). Anthropogenic sources often exhibit distinct $\delta^{15}N$ values. For example, the $\delta^{15}N$ values of synthetic fertilizers range from -4 to +4 ‰ (Heaton, 1986), animal wastes (manure and untreated sewage) typically range from +6 to +10 ‰, and treated sewage typically exceeds +10 ‰ (Kendall, 1998a). Atmospheric N_2 has a $\delta^{15}N$ signature of 0‰ (by definition) whereas newly fixed N has a value of -3 to 0‰ (Owens, 1988). These ranges in $\delta^{15}N$ may help to constrain N sources.

$\delta^{15}N$ values can also be used to gauge trophic ecology. Nitrogen isotopes become enriched through trophic transfer by enrichment factors of ~ 3.4 ‰. This helps to compute the trophic position of organisms within food webs. Similarly, plotting $\delta^{15}N$ against $\delta^{13}C$ value (biplot) has been used for

evaluating the impact of anthropogenic pressure (Fraser et al., 2024). This conveys the capacity to show the trophic niche of each organism and detect variability due to pollution stress.

Interpretation of isotope signatures in consumer organisms living in aquatic ecosystems requires careful consideration of trophic fractionation. Within this context, various aquatic organisms, including mangrove leaves, filter-feeding consumers, and fish, assimilate $\delta^{15}N$ signatures from their food sources into their tissues (Risk et al., 2009). Trophic fractionation refers to the alteration in isotopic composition as these signatures are transferred from one organism to another. Notably, there is an observed approximately 3.4 ‰ increase in $\delta^{15}N$ for each successive trophic level transfer within the food web (DeNiro and Epstein, 1978; Minagawa & Wada, 1984). In contrast to $\delta^{15}N$, the enrichment lower (~ 1 ‰) for $\delta^{13}C$. This enrichment phenomenon is integral to inferring the nutrient dynamics in aquatic ecosystems and food webs.

After accounting for trophic fractionation, the $\delta^{15}N$ measured in aquatic organisms can serve as a proxy for understanding biogeochemical cycling of nitrogen and its inputs, spatially and/or temporally (Costanzo et al., 2001; Vander Zanden et al., 2005). This isotopic tool can therefore aid in assessing the impact of sewage and fertilizer nitrogen sources on aquatic ecosystems.

1.1.3 Tracing nitrogen pollution in coastal environments: the versatility of $\delta^{13}C$ and $\delta^{15}N$ stable isotopes analyses

The $\delta^{15}N$ in bioindicator organisms has been used for mapping the spatial and temporal extent of N pollution (Dailer et al., 2010; Thibault et al., 2020; Umezawa et al., 2002). For example, Costanzo et al. (2001) used $\delta^{15}N$ in Moreton Bay, Australia to show the sources, extent, and fate of biologically available sewage-derived nitrogen in a coastal marine ecosystem. In addition to mapping $\delta^{15}N$ isotopes spatially, $\delta^{15}N$ preserved in accreting organisms such as corals has been

used to track sewage pollution histories through time. For example, Baker et al. (2013) used $\delta^{15}N$ preserved in gorgonian corals to show the impact of tourism on the nitrogen footprint of a Mesoamerican coral reef. Similarly, Sherwood et al. (2010) recorded land-based pollution load in Green Turtle Bay, Bahamas using gorgonian corals' $\delta^{15}N$. It has been noted that $\delta^{13}C$ and $\delta^{15}N$ in water columns and sediment reflect the integrated influence of biogeochemical processes (Ye et al., 2017).

Unlike other methods, such as direct measurement of seawater chemistry (e.g. NO_3^- and NH_4^+ concentrations) which are typically instantaneous or "snapshot" measurements, the value of $\delta^{13}C$ and $\delta^{15}N$ as a proxy or tracer lies in its ability to show integrated effects of N-sources, as recorded within the tissues of aquatic organisms and sediment. This makes it suitable for providing a time-integrated picture of the sources and histories of sewage N pollution. Hence $\delta^{15}N$ maps can be useful for understanding the sources of N pollution over large time and space scales relevant to pollution management.

1.1.4 Precision in sewage pollution assessment

Among many factors to consider when applying $\delta^{13}C$ and $\delta^{15}N$ stable isotope analyses to pollution management is the difference between particulate and dissolved inorganic N (DIN) (Sherwood et al., 2010). Sewage-derived particulate $\delta^{15}N$ values may be as low as 2‰ (Sweeney et al., 1980; Tucker et al., 1999) while sewage-derived DIN typically exceeds +6‰ (Böhlke et al., 2006; Dillon et al., 2007; Lindau et al., 1989). Also to be considered is the type of organism to be used as a bioindicator. The suitability of an organism for tracing of sewage impacts depends on its availability, animal characteristics and the goal of the research. Commonly available organisms such as fish, invertebrates (shrimps and crabs), and mangrove leaves have been widely utilized as bioindicators (Baeta et al., 2017; Horka et al., 2023; Nixon et al., 2007; Sherwood et al., 2010;

Umezawa et al., 2002b). Species with long lifespans are increasingly utilized as bioindicators (Sherwood et al., 2010). However, the choice of a suitable bioindicator depends significantly on the objective of the study. Organisms with short lifespans and high tissue turnover rates, such as mangrove leaves, are suited for characterizing short-term changes in N sources. In contrast, organisms with long lifespans and low tissue turnover rates, such as corals, are useful for providing longer-term perspectives.

1.1.5 Study area

Lagos lagoon is one of the largest among the many lagoons in the Barrier Lagoon Complex of the Gulf of Guinea (Ajao, 1996). It is located in Lagos, one of the most populated cities in West Africa with over 22 million inhabitants (Ezeudu et al., 2021). The lagoon lies between latitudes 6° 26′ and 6° 38′ N, and longitude 3° 23′ and 3° 43′ E. It is about 6400 km^2 in area and 285 km in the perimeter (as estimated from Google Earth). Lagos lagoon consists of many creeks such as Yewa, Badagry, Ologe, Iyagbe, Kuramo, Apese, Epe, and Mahin lagoons (Badejo & Alademomi 2014). These creeks have been separately referred to as lagoons in literature. However, there is a portion of the lagoon with the name, Lagos lagoon. Therefore, the use of the term Lagos lagoon in this study includes all these smaller lagoons. The lagoon is shallow with a depth-range of 2-10 m. However, Lagos Harbour (Commodore Channel) can be up to 30 m deep and represents the part of the lagoon that exchanges water with the Atlantic Ocean (Ajao, 1996; J. A. Nkwoji & Awodeyi, 2018).

1.1.6 Salinity distribution; temperature; freshwater sources

Ecological conditions in Lagos lagoon are strongly influenced by the wet (rainy) and dry seasons (Hill & Webb, 1958b; Nwankwo, 1996b). The wet season runs from May to October and the dry season from November to April (Onyema, 2007). The wet season has two peaks with the first

mostly in June and the second in September. Rainfall is abundant during the first half (May to October) but varies from one year to another (Hill & Webb, 1958). Salinity in the lagoon is controlled by seasonality in rainfall and fluctuates from freshwater (0.08) to brackish (17.32) water within the year and between locations (Webb, 1958; Botany & Onyema, 2018; Yakub et al. 2011; Nkwoji et al. 2010). The lagoon receives inputs from different creeks and rivers draining more than 103,626 km^2 of the country (Ajao, 1996). The population around the lagoon's watershed has grown rapidly and is unevenly distributed. The western side of the lagoon, where the city of Lagos is located, is more populated than the eastern side (see Fig. 1.2).

1.2 Thesis Outline

This thesis is comprised of two distinct chapters. Chapter 2 explores the nitrogen cycling in Lagos lagoon, with a specific focus on the measured $\delta^{13}C$ and $\delta^{15}N$ distribution as a function of space and time and is written as a manuscript suitable for submission for publication. Chapter 3 is presented as a technical report and compares the results of nutrient analyses of water samples from Lagos lagoon, Bedford Basin and reference materials conducted at the Dalhousie University and the University of Lagos (Unilag). It highlighted the logistical and analytical challenges facing international scientific cooperation and suggested possible measures to enhance the effectiveness of international collaboration in this area of research while moving towards establishment of a monitoring program for the lagoon.

Chapter 2

A Survey of Spatial-Temporal Variability of the Carbon and Nitrogen Isotopic Composition of Sediments and Biota of Lagos Lagoon, Nigeria.

2.1 Foreword

This chapter will form the basis of a manuscript to be submitted to a technical journal along with co-authors Juliet Igbo, Akeem Abayomi, Owen Sherwood, and Douglas Wallace. Initial study design and sampling strategies were designed by myself and led by me with collection assistance from each of the co-authors. The sampling logistics were coordinated by Juliet Igbo and Akeem Abayomi with financial assistance from Dalhousie University.

2.2 Highlights

1. Obtained the first carbon and nitrogen stable isotope data set from sediments and biota from Lagos lagoon.
2. $\delta^{13}C$ varied most strongly by location, with lower values (< -25 ‰) in the more freshwater influenced northern and eastern zones, and higher values (> -25 ‰) in the more marine influenced southern and western zones of the lagoon.
3. $\delta^{15}N$ varied most strongly by trophic position, following typical trophic fractionation patterns (+2.8 to 5.2 ‰ per trophic level) from primary producers through piscivorous consumers.
4. Calculated baseline $\delta^{15}N$ averaged (5.2 ± 2.6 ‰) in most of the lagoon, within the range of natural marine nitrate and terrestrial soils.
5. The shallow depth and short residence time of waters in Lagos lagoon may help to mitigate anthropogenic disturbances to the lagoon's N cycle.

2.3 Abstract

Lagos lagoon, a vital coastal ecosystem in West Africa, sustains the livelihoods of millions of people amidst escalating pollution threats stemming from dense human habitation in its watersheds. Despite facing severe degradation and diminished ecosystem services, the lagoon lacks a coordinated water quality monitoring program. This study employed stable isotope analyses of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) in sediments and representative biota to assess spatial and seasonal variabilities in nutrient sources and trophic dynamics. Sediments and biota (mangrove leaves, invertebrates, and fish) were collected from four zones spanning densely populated and relatively less populated areas of the lagoon during dry (December) and rainy (August) seasons. The $\delta^{13}C$ of sediments and biota was generally lower (< -25 ‰) in the more freshwater influenced northern and eastern zones of the lagoon, and higher (> -25 ‰) in the more marine influenced western and southern zones. The observed distribution of $\delta^{13}C$ was therefore attributed to relative differences in terrestrial vs. marine sources of carbon. The $\delta^{15}N$ of sediments and biota was most strongly impacted by trophic effects and increased predictably with known or inferred trophic position. Compared to spatial and trophic effects, seasonality had relatively minor and inconsistent effects on $\delta^{13}C$ and $\delta^{15}N$. Calculated baseline $\delta^{15}N$ averaged 5.2 ± 2.6 ‰ for the northern, eastern and western zones and was lower (1.6 ± 1.3 ‰) in the southern zone. The baseline $\delta^{15}N$ values were all within range of natural seawater nitrate and terrestrial soils, which made it difficult to attribute specific anthropogenic effects on nitrogen cycling in the lagoon. Overall, these data may serve as an important temporal baseline for future monitoring in Lagos lagoon. Going forward, targeted analysis of select bioindicator taxa over wider ranges in space and time is recommended.

2.4 Significance

Understanding the integrated level of pollution and its impact on the food web remains a critical challenge for Lagos lagoon. Effective planning for pollution management in the lagoon necessitates a comprehensive understanding of these dynamics, which can be achieved through the implementation of a coordinated monitoring program. Establishing baseline pollution levels is a crucial initial step, often requiring exploratory surveys. In December 2022 and August 2023, we conducted sampling of biota and sediment from highly urbanized and relatively less urbanized zones of Lagos lagoon for stable isotope analyses, aiming to characterize the seasonal and spatial variability of isotope data, nutrient inputs, and their impact on the food web. Above all, the isotope data provides a critical foundation for the integrated assessment of nutrient cycling in Lagos lagoon.

2.5 Introduction/Background

Globally, eutrophication is a major threat to coastal marine ecosystems (Heath, 2008; Tuholske et al., 2021). Like many other coastal areas, Lagos lagoon is threatened by excessive nutrient input. Unfortunately, unlike similar environments in the developed world such as Venice lagoon (Solidoro et al., 2010) and Mar Menor lagoon, Lagos lagoon lacks a coordinated monitoring program and appropriate wastewater treatment, despite increasing threats from the rapidly growing population around Lagos city (22 million people; (Ezeudu et al., 2021) projected to reach 45 million people by 2070 (United Nations, 2018). Coordinated monitoring not only plays an essential role in informing policies and management strategies for sustaining lagoon ecosystem services but also serves as a basis for evaluating the efficacy of any implemented policies and strategies aimed at reducing lagoon pollution (Borja & Elliott, 2013). The collection of exploratory data to define a baseline is a first step towards design and establishment of a monitoring program. Several prior studies have attempted to measure pollution levels in Lagos lagoon and identify their sources (e.g. Adesalu et al., 2010; Nkwoji & Awodeyi, 2018); however, most of these measurements have been based on instantaneous sampling that has been scattered in space and time. An updated study tracking pollution signature over time and space in Lagos lagoon at consistent locations is required to guide the design of a longer-term monitoring program.

2.5.1 Pollution threats to Lagos lagoon

The ability of Lagos lagoon to provide services such as source of food, water, recreation and means of transportation is increasingly threatened by coastal development and, especially, pollution. The activities of the burgeoning human population such as domestic upkeep, agricultural land use of the catchment areas, and urbanization introduces large volumes of pollutants into the lagoon annually (Clarke et al., 2020; Nkwoji et al., 2020; Nwankwo, 2004). Human-sourced pollution can

be classified into various categories such as oil spills, non-point sources, sewage, and industrial effluents (Vikas & Dwarakish, 2015). Sewage is undoubtably a major source of pollution in Lagos lagoon. Sewage can be broken down within the lagoon water, it still causes many significant adverse effects on marine life.

Over the last few decades, the human population, and the number of industries within Lagos city and around the lagoon have grown rapidly and are still growing at an increasing rate according to World Population Review (2024). The increase in population is accompanied by subsequent increases in sewage generation compounded by the lack of adequate treatment plants (Omololu & Lawal, 2013). The increase in sewage generation coupled with inadequate waste management infrastructure (Ike et al., 2018) results in the direct and indirect discharge of untreated sewage and other effluents from homes and workplaces into the lagoon (Ajao, 1996). There has also been increased fertilizer usage for agriculture and growing industrial effluent generation.

Although there can be many sources of pollution to the lagoon, sewage and agricultural runoff are the major pathways through which human activities introduce pollutants (Longe & Ogundipe, 2010; Nubi et al., 2008). The level of pollutants introduced from sewage can be directly linked to human population (Milledge et al., 2018). The amount of pollution introduced by agricultural runoff is mainly linked to the amount of agricultural fertilizer usage (Nixon et al., 2007). This makes the level of sewage-driven pollution an important proxy for determining the impact of population increase on the lagoon ecosystem. Studies focusing on sewage as index for assessing human impacts on coastal marine ecosystems have long been documented (Bricker et al., 1999; Risk, Lapointe, et al., 2009; Sherwood et al., 2010; Smith, 2003).

Sewage and other effluents introduce high concentrations of N mainly in the form DON which causes eutrophication and leads to algal blooms, low oxygen (hypoxia), death of fish and seagrass, and reduction in essential lagoon habitats (Rabalais et al., 2014). As the human population increases, the amount of DON delivered from sewage increases. The input of N (DON and DIN) serves as an indicator of pollution levels in water bodies including coastal lagoons (Risk et al., 2009). Again, ^{15}N and ^{13}C levels can also reveal the impact of pollution on trophic structures (Costanzo et al., 2001). Measuring the stable isotopes of ^{15}N and ^{13}C makes it possible to obtain an integrated view to, for example, distinguish sewage sources of N from other sources (Risk et al., 2009).

2.5.2 Application of carbon and nitrogen stable isotopes to the study of pollution in marine environments

Stable isotope analyses are a commonly used tool in ecological studies for elucidating the origins, pathways, and fates of land-derived pollutants, including their impacts on trophic structure (Evershed et al., 2008; Perkins et al., 2014; Savage, 2005; Sherwood et al., 2010). Notably, the natural abundance stable isotope ratios of N ($\delta^{15}N$) have been applied in pollution studies (Costanzo et al., 2001; Fry, 2006; Horka et al., 2023). $\delta^{15}N$ has proven effective in tracing the impact of sewage on coastal water bodies, including lagoons (Baker et al., 2013; Tuholske et al., 2021). Its utility in environmental monitoring is rooted in the differential fractionation of isotopes during various biological and microbial processes (Costanzo et al., 2001). This results in sewage becoming isotopically enriched, particularly with respect to $\delta^{15}N$, because of kinetic isotope fractionations associated with volatilization of ammonia and other N transformations (Heaton, 1986; Kendall, 1998b).

The $\delta^{15}N$ of primary producer aids in identifying specific nitrogen sources in nutrients that form the foundation of the food web (Zanden & Rasmussen, 2001). This relies on the principle that different nitrogen sources have unique ranges of $\delta^{15}N$ (McClelland et al., 1997). For example, atmospheric N_2 has, by definition, a $\delta^{15}N$ of 0 ‰, whereas oceanic nitrate (NO_3) typically has a $\delta^{15}N \sim 4.8$ ‰ (Sigman et al., 2000). Anthropogenic sources of nitrogen can also have distinct $\delta^{15}N$ values: synthetic fertilizers range from -4 to +2 ‰, while animal wastes like manure and untreated sewage range from +6 to +10 ‰ (Kendall, 1998c; Waldron et al., 2001) although observations indicate that untreated sewage can also possess values as low as +2 ‰ (Sweeney & Kaplan, 1980). Secondly, differences in $\delta^{15}N$ between a consumer and its prey can be employed to quantify an organism's trophic position within a food web, as the $\delta^{15}N$ in consumer tissues consistently becomes enriched with each successive trophic transfer (DeNiro & Epstein, 1981; Minagawa & Wada, 1984). Furthermore, combining an organism's stable isotopes of $\delta^{13}C$ and $\delta^{15}N$ also provides insight into both sources and impacts on food web trophic interaction within ecological communities (Peterson et al., 1987).

Differential $\delta^{13}C$ signatures in various organic matter pools within ecosystems also provide a means to track and quantify dietary origins (Post, 2002). Specifically in coastal ecosystems, $\delta^{13}C$ can be used to distinguish between terrestrial and marine carbon sources, as terrestrial carbon commonly exhibits a relatively depleted $\delta^{13}C$ signature ($\delta^{13}C \sim$ -28‰; Fry, 2006), when compared to marine algae ($\delta^{13}C \sim$ -22‰; (Duarte et al., 2018).

2.5.3 Study area

Lagos lagoon (Fig. 2.1) is one of the largest tidal estuaries in the Barrier Lagoon Complex of the Gulf of Guinea (Ajao, 1996). It is located next to Lagos, one of the most populated cities in West Africa with over 22 million inhabitants (Ezeudu et al., 2021). The lagoon lies between latitudes 6°

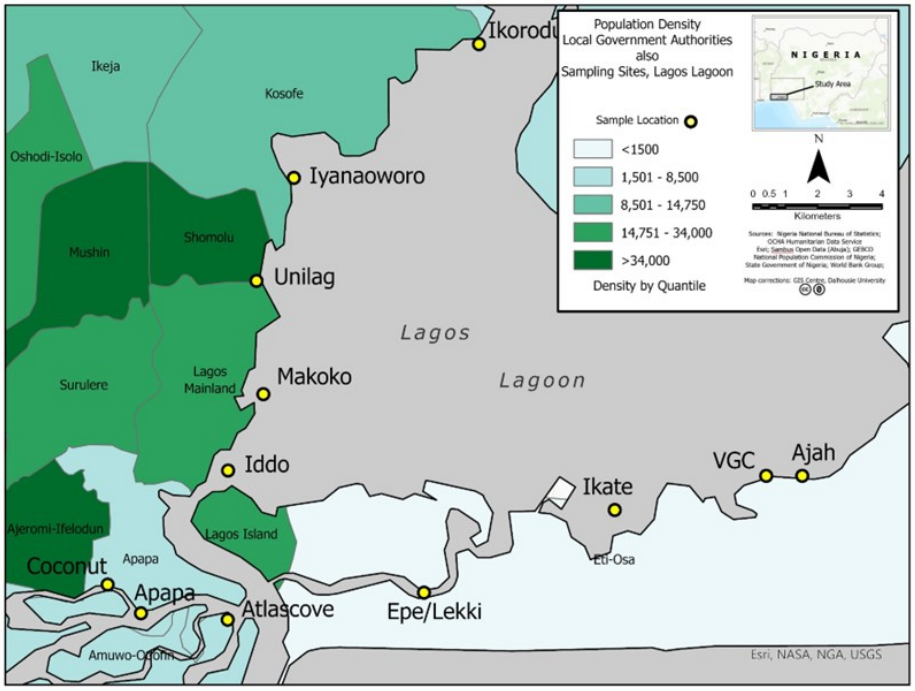


Figure 2.1: *Map of Lagos lagoon showing watershed population distribution and study sites.*

26′ and 6° 38′ N, and longitude 3° 23′ and 3° 43′ E. It is about 6400 km2 in area and 285 km in perimeter. Lagos lagoon is fed by many creeks and inlets such as Yewa, Badagry, Ologe, Iyagbe, Kuramo, Apese, Epe, and Mahin, which are sometimes referred to as "lagoons" in the existing literature (Badejo & Alademomi, 2014). In the present study, "Lagos lagoon" refers to the main estuary together with these creeks and inlets. Bathymetry in the lagoon is generally shallow and ranges between 2-10 m. However, Lagos Harbour (specifically the Commodore Channel) may reach depths of up to 30 m at the point where the lagoons empty into the Atlantic Ocean (Ajao, 1996; Nkwoji & Awodeyi, 2018).

The lagoon's ecological condition is controlled by two major seasons, wet (rainy) and dry (Hill & Webb, 1958; Nwankwo, 1996). The wet season runs from May to October and the dry season from November to April (Onyema, 2007). The wet season has two peaks, with the first occurring mainly in June and the second in September. Rainfall is abundant (250 mm – 500 mm; Ezeh et al., 2016)

during the first half (May to October) but may vary from one year to another (Hill and Webb, 1958). Salinity is controlled by seasonality in rainfall and fluctuates from 0.08 to 17.32 within the year (Webb, 1958; Yakub et al., 2011; Nkwoji et al., 2010). The lagoon receives inputs from different creeks and rivers draining more than 100,000 km2 of the country (Ajao, 1996). The population within the lagoon's watershed has grown rapidly, with most of the population and population growth concentrated along the western side of the lagoon. (Nkwoji, 2011).

2.5.4 Previous work

The increasing pollution threat to the lagoon has attracted research attention over the years (Adesalu et al., 2010; Ajao, 1996; Akagha et al., 2020; Obi et al., 2016; Nkwoji & Awodeyi, 2018; Nkwoji et al., 2010; Nkwoji et al., 2020; Oladosu et al., 2017; Olayinka et al., 2016; Onyema, 2007; Oyatola et al., 2021; Yakub et al., 2011). Some studies attempted to measure the level of specific pollutants in Lagos lagoon and identify their sources (Adesalu et al., 2010; Nkwoji & Awodeyi, 2018). However, most of these measurements were based on instantaneous measurements, were scattered in space and time (see Fig. 1.2), and only provided snapshots of pollution condition. The available measurements do not allow for integrated or systematic measurement of eutrophication over time and space. A systematic, integrated and coordinated measurement approach is required for the planning, establishment, and assessment of effective management.

2.5.5 Objectives

This study aims to survey carbon and nitrogen stable isotopes in sediments and biota of Lagos lagoon and determine they how they are influenced spatially and temporally. Ideally, this would require an extensive program of regular time- and space- resolved sampling and analyses

throughout the lagoon, as well as monitoring of inputs from key discharge points. This is not within reach at the present time but could be a future effort that can be built off this initial work. Therefore, this pilot study will use nitrogen and carbon isotopes as tracers of integrated nutrient inputs, their geographical distribution in two seasons of the year and possible impacts on the food web trophic structure.

Focusing on Lagos lagoon, the specific objectives of this study include:

i. to measure the spatial variability in $\delta^{13}C$ and $\delta^{15}N$ across urbanization gradient during both the wet and dry seasons
ii. to evaluate potential impacts of pollution on food web trophic structure between highly impacted and less impacted zones of the lagoon**.**

2.6 Sample Collection and Analytical Methods

Sample collection for the study was conducted in collaboration with two partner institutions in Nigeria: The National Institute of Oceanography and Marine Research (NIOMR) and the University of Lagos (Unilag).

2.6.1 Field work

Sampling was conducted once in each of the dry (December 2022) and wet seasons (August 2023). Four (4) zones and at least one station from each zone of the lagoon were sampled (Fig. 2.1). The number of sampling stations varied between zones and seasons. There were 10 and 12 stations sampled in the dry and rainy seasons, respectively. Biota (crab, fish, shrimp, macrophytes) and sediments were collected. Biota samples were collected from at least one station per zone, while sediment samples were collected from all the stations (Table 2.1). The zones and sampling stations

Table 2.1: List of field stations with surface water temperature, salinity, number of samples by type and season, and field observations.

Zone	Station Name	Stn. #	Lat. (°N)	Long. (°E)	Temperature		Salinity		Samples (n = #)								Field observations
									Sediment		Macro-phyte		Invert-ebrate		Fish		
					Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	
North	Ikorodu	1	6.6050	3.4703	30.2	27.4	4.7	0.1	1	1	1	-	2	-	9	7	Sand dredging surrounded by mangroves with low tides.
West	Iyanaoworo	2	6.5470	3.4138	30.8	27.7	8.9	0.2	1	1		-	-	-	-	-	Presence of water hyacinth surrounded by mangroves.
	Unilag	3	6.5212	3.4056	30.1	27.9	11.1	0.2	1	1		-	-	-	-	-	Presence of fishing activities with large deposit of logs on the surface of water.
	Makoko	4	6.4963	3.4003	29.9	28.2	12.5	0.3	1	1	-	1	3	3	13	2	Presence of fishing activities, coastal settlement with sand dredging activities with large deposit of logs on the surface of water.
	Iddo	5	6.4682	3.3846	29.2	27.7	18.2	5.4	1	1	1	-	-	-	-	-	Close by mechanic workshop with a nearby dumpsite.
South	Apapa	6	6.4275	3.3667	29.6	28.5	21.0	5.0	1	1	-	-	2	1	8	6	Presence of shipping activities.
	Coconut	7	6.4373	3.3598	30.8	28.1	19.4	5.2	1	1	-	-	-	-	-	-	Surrounded by industrial activities with presence of shipping and transportation activities as well as marine litters/debris.
	Atlas Cove	8	6.4299	3.3978	29.6	28.5	21.0	5.1	1	1	-	-	-	-	-	-	Point of exchange between Lagos lagoon and Atlantic Ocean.
East	Epe/ Lekki	9	6.4375	3.4515	30.3	28.3	14.1	1.5	1	1	-	-	3	2	5	7	Marine litters/debris surrounded by domestic activities such as eateries, industrial activities and land reclamation.
	Ajah	10	6.4798	3.5068	29.8	28.1	5.0	0.3	1	1	1	-	-	-	-	-	Presence of sand dredging machines and pipelines.
	VGC	11	6.4702	3.5542	n/a	28.0	n/a	0.6	-	1	-	-	-	-	-	-	Presence of marine litters/ debris and sand dredging activities.
	Ikate	12	6.4693	3.5367	n/a	28.3	n/a	0.4	-	1	-	-	-	-	-	-	Marine litters/debris with the presence of domestic activities.
Average ± St.Dev. / Sample Count					30.0 ± 0.5	28.0 ± 0.3	13.6 ± 6.2	2.0 ± 2.4	10	12	3	1	10	6	35	22	

were chosen in collaboration with NIOMR and Unilag and represent stations upon which these institutions have based their previous studies of the lagoon. Study sites were chosen to represent highly urbanized and relatively less urbanized areas of the lagoon, yet still be logistically accessible during a one-day sampling trip.

The organisms sampled were common ones found across the lagoon. Organisms with high tissue turnover rates were chosen over low tissue turnover once as they are good bioindicators of the integrated level of sewage impact over short temporal period on the lagoon (Browning et al., 2014; Risk, Sherwood, et al., 2009). The multi-species sampling aimed to provide an integrated measurement of the accumulated level and mapping of the sewage N distribution of the lagoon. The sampling approach used here is recommended for establishing a monitoring program for water bodies such as Lagos lagoon where pollution has long preceded monitoring (U.S. Environmental Protection Agency – EPA, 2002). Where possible, replicate samples from same species were collected and the lower tail muscle tissues excised for stable isotope analyses. For the dry season sampling, 35 fish, 6 crabs, 6 shrimp, 3 samples of mangrove leaves (water hyacinth), and 10 sediment samples were collected for the study. For the rainy season, 22 fish, 1 crab, 5 shrimp, and 1 water hyacinth sample were collected (Table 2.1). In both seasons, samples varied both in group and species per station, with some groups and species cutting across all the stations (Tables 2.1).

Sampling was conducted as follows: sediment and mangrove leaves samples were collected from a speedboat across the 4 zones and at other selected sites of the lagoon. The collection of sediment was performed using a manually operated sediment grab and water hyacinth were collected by direct detachment. For the dry season sampling, biota samples (fish, crab, and shrimp) were purchased from landing sites in each of the zones. In the rainy season, biota samples were collected in-situ. This was possible through arrangements with local artisanal fishers from each zone.

2.6.2 Sample preparations and laboratory analyses

Upon collection in the field, the fish, crab, shrimp, water hyacinth and sediment samples from each zone were placed in zip lock bags, stored in a cooler containing ice blocks, and transported to the NIOMR biological laboratory for processing. In-situ measurements of water temperature, AND salinity were undertaken at each sampling location using a Horiba U-52 multiparameter instrument by directly lowering the instrument's probe into the surface of the water. Processing at NIOMR consisted of extraction of tissue samples, sediment sub-sampling, and freeze drying. For tissue extraction, muscle tissue was taken from the tail section of the fish, the crusher claw muscle of the crab, and internal tissues of the shrimp were collected. The tail section of fish was selected due to its high protein content and low turnover rate (Gorokhova & Hansson, 1999). For the crab and shrimp, the crusher claw muscle and internal tissues were selected due to their high protein and low lipid content (Warnakulasooriya et al., 2017). The biota samples along with the detached clippings of water hyacinth and sediment samples were freeze-dried at -60° C for 48h and placed in well-labelled zip lock bags. The freeze-dried samples of biota were partially crushed, and along with water hyacinth and sediments were transported by air freight to Dalhousie University for stable isotope analyses.

At Dalhousie University, samples were stored in the freezer pending analyses. Prior to analyses, the water hyacinth and biota samples were ground using a mortar and pestle or coffee grinder into a fine, homogenous powder. Aliquots of each sample were weighed to an average of 1.0 ±0.5 mg for biota and water hyacinth, and 30.0 ±0.5 mg for sediment in tin capsules.

The individual samples were analyzed for C and N contents, and $\delta^{13}C$ and $\delta^{15}N$ using an Isotope Ratio Mass Spectrometer (IRMS) at the CERC-Ocean Laboratory at Dalhousie. Stable isotope

measurements are reported using the delta notation in parts per thousand (‰) as in equation (Eq. 2):

$$\delta^{13}C \text{ or } \delta^{15}N = [(R_{sample}/R_{standard}) - 1] \times 1000 \quad [2]$$

where R is the $^{13}C/^{12}C$ or $^{15}N/^{14}N$ ratio and the standard is Vienna PeeDee Belemnite (VPDB) for $\delta^{13}C$ and atmospheric N_2 for $\delta^{15}N$. Analytical precision, measured as the standard deviation of repeat analyses of standards, averaged 0.04‰ and 0.08‰ for $\delta^{13}C$ and $\delta^{15}N$, respectively. Measured $\delta^{13}C$ values were not corrected for lipid content (e.g. Post et al., 2007), as C:N in the biota values were consistently 3.2 except for macrophytes and oysters (Table 2.3).

2.6.3 Statistical analyses

Statistical analysis was conducted in "R" (version 4.4.0) with RStudio (version 2024.04.1) using the base "stats" package. Linear models (linear regression, analysis of variance (ANOVA)) were coded using the "lm" function. Model residuals were tested for assumptions of normality and heteroscedasticity using diagnostic (residuals and quantile-quantile) plots. If outlier data points were indicated in the diagnostic plots, the models were re-run, omitting outliers. Statistical significance was assessed at the 5% level of probability ($p \leq 0.05$). Factor-level ANOVA effects were further tested for using Tukey's Honestly Significant Differences (HSD) tests.

2.7 Results

2.7.1 Environmental conditions

Surface water temperatures at the sampling stations averaged 30.0 ± 0.5 ºC during the dry season and 28.0 ± 0.3 ºC during the wet season. Surface salinity averaged 13.6 ± 6.2 during the dry season and 2.0 ± 2.4 during the wet season (Table 2.1). Salinity increased from fresher values in the northern and eastern zones to more saline values in the western and southern zones where lagoon water mixes with the Atlantic Ocean (Fig. 2.2a). Anthropogenic activities were observed at most locations. Activities with potential effects on N cycling included dense human habitation (Station 4, 9, 12), fishing (3, 4), logging activities (3, 4), dumpsites and debris (5, 7, 9, 11, 12), and shipping and industrial activities (6, 7, 9, 10) (Table 2.1).

Table 2.2 Sediment C:N, $\delta^{13}C$ and $\delta^{15}N$ by station and season.

Station #	C %		N %		C:N ratio		$\delta^{13}C$ (‰)		$\delta^{15}N$ (‰)	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
1	1.05	1.30	0.05	0.09	19.4	14.5	-27.5	-26.3	1.2	5.7
2	5.15	0.82	0.43	0.05	12.1	16.8	-27.8	-24.4	6.3	3.6
3	2.89	1.76	0.26	0.14	11.3	12.6	-27.0	-25.8	7.1	5.2
4	1.75	0.97	0.15	0.09	11.7	11.0	-24.4	-26.8	6.9	4.0
5	0.34	2.06	0.03	0.15	12.7	13.8	-17.9	-24.2	-1.5	7.8
6	1.25	0.62	0.09	0.03	14.5	18.5	-23.7	-25.0	4.2	1.2
7	1.42	0.27	0.15	0.02	9.2	11.2	-18.1	-24.7	3.4	-0.2
8	0.17	1.05	0.00	0.07	34.2*	14.5	-8.59*	-23.5	1.0	4.5
9	0.61	3.80	0.05	0.28	12.9	13.6	-26.5	-22.0	2.0	8.8
10	1.19	1.61	0.09	0.09	13.1	17.5	-26.5	-28.0	4.2	3.9
11	n/a	2.10	n/a	0.15	n/a	14.1	n/a	-27.1	n/a	4.7
12	n/a	1.38	n/a	0.07	n/a	20.1	n/a	-26.3	n/a	4.6
Mean	1.58	1.48	0.13	0.10	13.0	14.8	-24.4	-25.3	3.5	4.5
St.Dev.	1.47	0.92	0.13	0.07	2.8	2.8	3.8	1.7	2.8	2.4

* Affected by high carbonate abundance; omitted from subsequent analyses

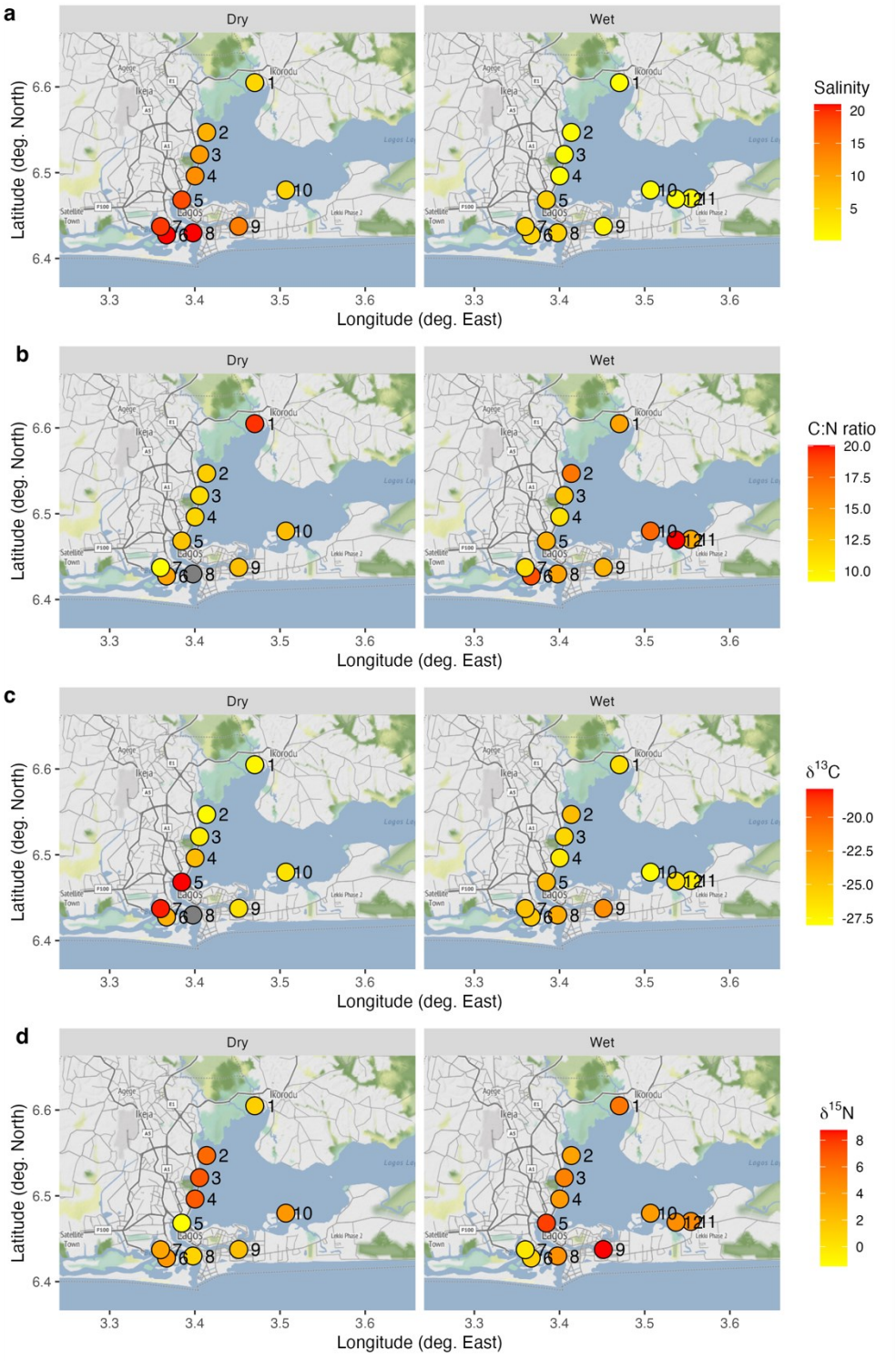


***Figure 2.2**: Spatial distribution of surface water salinity (a), sediment C:N (b), $\delta^{13}C$ (c) and $\delta^{15}N$ (d) in the dry and wet seasons.*

2.7.2 Sediment geochemistry

Sediment C:N, $\delta^{13}C$ and $\delta^{15}N$ data by season and sampling location are listed in Table 2.2. Two of the 12 locations (VGC and Ikate) were sampled only in the wet season. One of the samples (Station 8 (Atlas Cove) during the dry season) had abundant carbonate, generating unreasonable C:N and $\delta^{13}C$ values which were excluded from subsequent analysis. Fig. 2.2 shows the spatial distribution of C:N, $\delta^{13}C$ and $\delta^{15}N$ in the dry and wet seasons in relation to surface water salinity. C:N varied from 12.5 to 20.0. In general, C:N was highest at Ikorodu (northern) and Epe (eastern) and progressively lower toward the southern sites where the lagoon waters exchange with the Atlantic. $\delta^{13}C$ ranged from -28 ‰ to -22 ‰, and varied spatially opposite to that of C:N with lighter values in the north and east and heavier values in the south. Sediment $\delta^{15}N$ ranged from 2 ‰ to 8 ‰ with heavier values mostly in the western sites. Paired t-test analysis showed that there was no consistent effect of season on any of C:N ($p = 0.37$), $\delta^{13}C$ ($p = 0.13$) or $\delta^{15}N$ ($p = 0.23$). Therefore, the sediments were grouped by season in subsequent analysis.

To further explore environmental drivers of sediment biogeochemistry, C:N, $\delta^{13}C$, and $\delta^{15}N$ are plotted against surface water salinity in Fig. 2.3. Sediment C:N decreased and $\delta^{13}C$ increased, both weakly but significantly at the $p < 0.05$ level, in relation to surface water salinity. Sediments with lower C:N and heavier $\delta^{13}C$ approach the global accepted endmember for marine organic matter (C:N ~3-9; $\delta^{13}C$ ~22 ‰); values with higher C:N and lower $\delta^{13}C$ approach the endmember for terrestrial organic matter (C:N ~20; δ13C ~32) (Azzurro et al., 2007; Brodie et al., 2011; Finlay & Kendall, 2008; Vizzini et al., 2005). The data therefore appear to reflect mixing between terrestrially derived organic matter (higher CN; lower $\delta^{13}C$) in the more freshwater influenced northern and eastern stations, and marine derived organic matter (lower CN; higher $\delta^{13}C$) in the marine influenced western and southern stations.

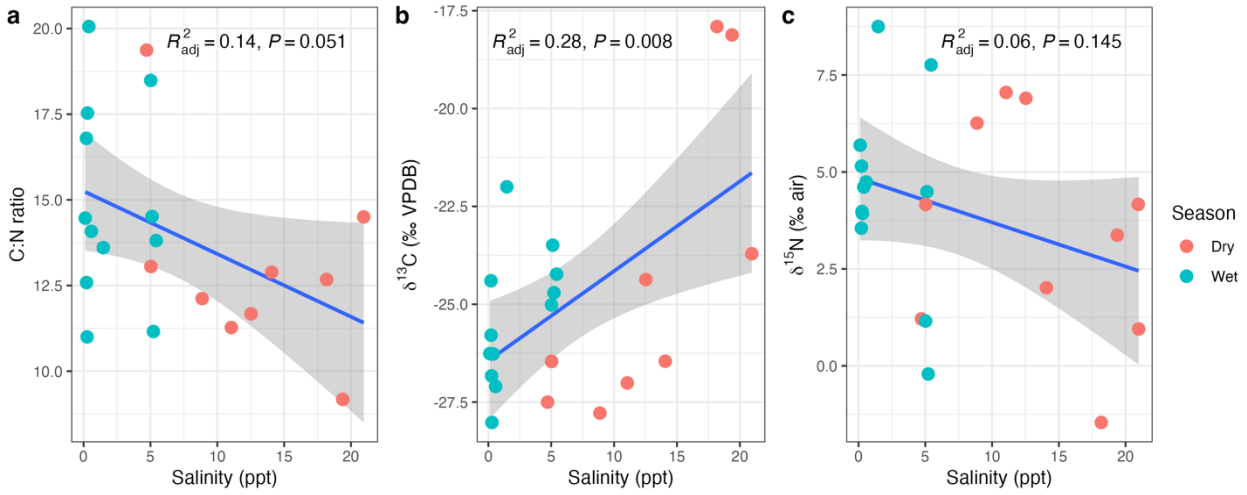


Figure 2.3: *Plots of sediment C:N (a), $\delta^{13}C$ (b) and $\delta^{15}N$ (c) vs salinity. r^2 and p-values refer to linear regressions in each plot, irrespective of season.*

Sediment $\delta^{15}N$ was uncorrelated with salinity at the p = 0.05 significance level (Fig. 2.3c) but was highly correlated with the N content of the sediment ($\delta^{15}N = 2.1 \cdot \log(N) + 9.4$, $r^2 = 0.62$, $p < 0.001$; Fig. 2.4). This result may indicate that higher N load into the lagoon sediments is associated with elevated $\delta^{15}N$ signatures. Sediments with higher N contents and heavier $\delta^{15}N$ were located mostly near Lagos city in the west zone (stations 2,3,4,5) and near Epe/Lekke in east zone (station 9). Sediments with lower N contents and lighter $\delta^{15}N$ were in the southern zone were lagoon waters exchange with Atlantic waters and in the northern location (Fig. 2.2d).

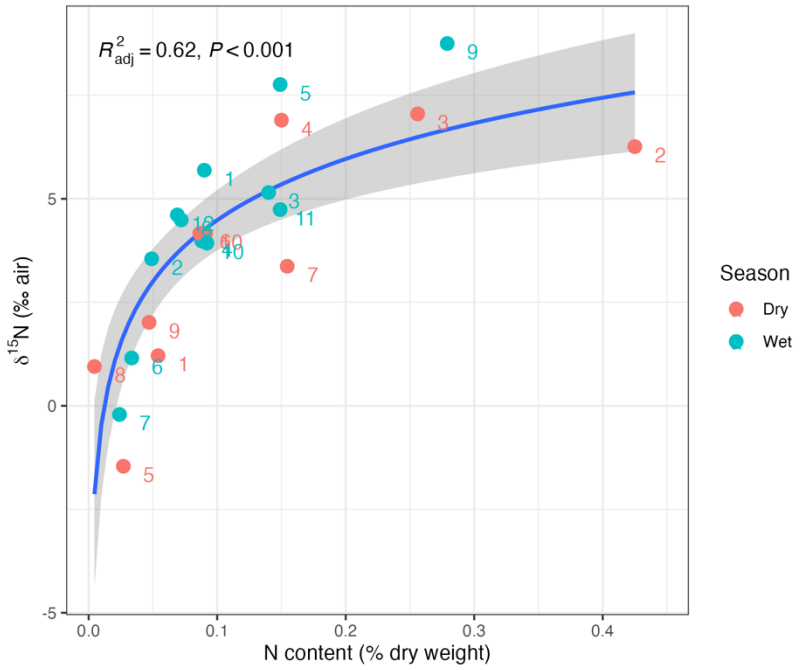


Figure 2.4: *δ^{15}N vs N content of the sediments for the dry and wet season. Regression fit is through all data irrespective of seasons. Numbered labels refer to collection stations.*

2.7.3 Stable isotopic variability in biota

Table 2.3 summarizes the C:N, δ^{13}C, and δ^{15}N of each species of biota sampled in Lagos lagoon averaged across seasons and zones. The C:N values across all biota excluding macrophytes averaged 3.4 ± 0.68, consistent with expected C:N values for muscle protein. The C:N for macrophytes averaged 9.2 ± 1.5. which is consistent with the C:N values of vascular plants. δ^{13}C exhibited a wide range of values from -32 ‰ (blackchin tilapia) to -15 ‰ (water snail). The distribution of δ^{15}N values among biota exhibited typical trophic fractionation effects, with lowest values in primary producer (macrophytes) and increasing through secondary and higher consumer invertebrates and fish (Fig. 2.5).

Table 2.3: Summary of biota sampled in Lagos lagoon grouped by species with literature-derived trophic positions (TP) and corresponding trophic guild (PP: primary producer; HC: herbivorous consumer; OC: omnivorous consumer; PC: piscivorous consumer), and mean measured C:N ratios, $\delta^{13}C$, and $\delta^{15}N$ across all zones and seasons. Uncertainties are reported as standard errors for TP and standard deviations for all other parameters.

Type	Common Name	Species	TP	Guild	N	C:N ratio	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)
Macrophyte	Hyacinth	*Eichhornia crassipes*	1	PP	4	9.2 ± 1.5	-30.3 ± 1	4.9 ± 4.5
Invertebrate	Crab	*Callinectes amnicola*	3 ± 0.5 [1]	OC	7	3.1 ± 0.1	-24 ± 3.5	12 ± 2
Invertebrate	Giant water prawn	*Macrobrachium sp.*	2.2 ± 0.08 [2]	HC	2	3.3 ± 0.1	-25.7 ± 0	11.2 ± 0.5
Invertebrate	Oyster	*Crassostrea gasar*	2 ± 0 [2]	HC	1	6.2	-24.6	10
Invertebrate	Pink shrimp	*Penaeus notialis*	2.5 ± 0.5 [2]	HC	4	3.1 ± 0.0	-21.2 ± 1.4	9 ± 0.4
Invertebrate	Water Snail	*Neritina glabrata*	2.2 ± 0.2 [2]	OC	2	3.2 ± 0	-15.4 ± 0.3	11.7 ± 0.3
Invertebrate	Tiger prawn	*Penaeus monodon*	3 ± 0.5 [2]	OC	5	3.2 ± 0.1	-29 ± 4.2	8.8 ± 2.1
Fish	Aba	*Gymnarchus niloticus*	3.7 ± 0.6 [3]	PC	1	3.2	-31.9	8.7
Fish	Atoko	*Liza grandisquamus*	2.5 ± 0.2 [3]	OC	3	3.2 ± 0.1	-23.6 ± 3.4	9.3 ± 1
Fish	Barracuda	*Sphyraena barracuda*	4.5 ± 0.6 [3]	PC	6	3.2 ± 0.1	-20.3 ± 4.3	13.2 ± 1.7
Fish	Blackchin tilapia	*Sarotherodon melanotheron*	2.2 ± 0.1 [3]	HC	2	3.2 ± 0.1	-32.1 ± 2.4	10.3 ± 4.0
Fish	Bobo croaker	*Pseudotolithus elongatus*	4.1 ± 0.7 [3]	PC	3	3.3 ± 0.2	-20.8 ± 3.1	15.2 ± 0.3
Fish	Bonga shad	*Ethmalosa fimbriata*	2.5 ± 0.3 [3]	OC	6	3.6 ± 0.6	-26.3 ± 2.4	13.5 ± 0.9
Fish	Catfish	*Chrysichthys nigrodigitatus*	3.17 ± 0.4 [3]	PC	4	3.3 ± 0.1	-28.3 ± 4.5	11.9 ± 3
Fish	Electric Catfish	*Malapterurus electricus*	2.9 ± 0.4 [3]	PC	1	3.3	-21.6	12.4
Fish	Grunt	*Pomadasys jubelini*	3.6 ± 0.5 [3]	PC	3	3.2 ± 0.1	-23.3 ± 2.7	12.8 ± 1.5
Fish	Jackfish	*Caranx hippos*	3.83 ± 0.7 [3]	PC	1	3.2	-17.8	14.2
Fish	Ladyfish	*Elops lacerta*	4.2 ± 0.8 [3]	PC	2	3.2 ± 0.1	-23.4 ± 3.5	11.9 ± 3.3
Fish	Moony fish	*Monodactylus sebae*	3.9 ± 0.6 [3]	PC	2	3.4 ± 0.4	-25.2 ± 1.7	16.7 ± 0.8
Fish	Grey mullet	*Mugil cephalus*	2.5 ± 0.2 [3]	OC	2	3.2 ± 0	-19.4 ± 3.1	12.0 ± 0.0
Fish	Atoko	*Liza grandisquamus*	2.5 ± 0.2 [3]	OC	3	3.2 ± 0.1	-23.6 ± 3.4	9.3 ± 1
Fish	Red Snapper	*Lutjanus agennes*	4.0 ± 0.6 [3]	PC	3	3.2 ± 0	-22.5 ± 4.9	13.6 ± 1.7
Fish	Redbelly tilapia	*Tilapia zillii*	2.5 ± 0.1 [3]	OC	8	3.2 ± 0.1	-22.5 ± 2.2	13.4 ± 1.3
Fish	Threadfish	*Polydactylus quadrifilis*	4 ± 0.7 [3]	PC	1	3.2	-25.7	15.7
Fish	unknown fish	n/a	n/a	n/a	7	4.6 ± 2	-30 ± 2.2	8.3 ± 2.6

[1] *Udoh & Jimmy, 2015*
[2] *sealifebase.org*
[3] *fishbase.org*

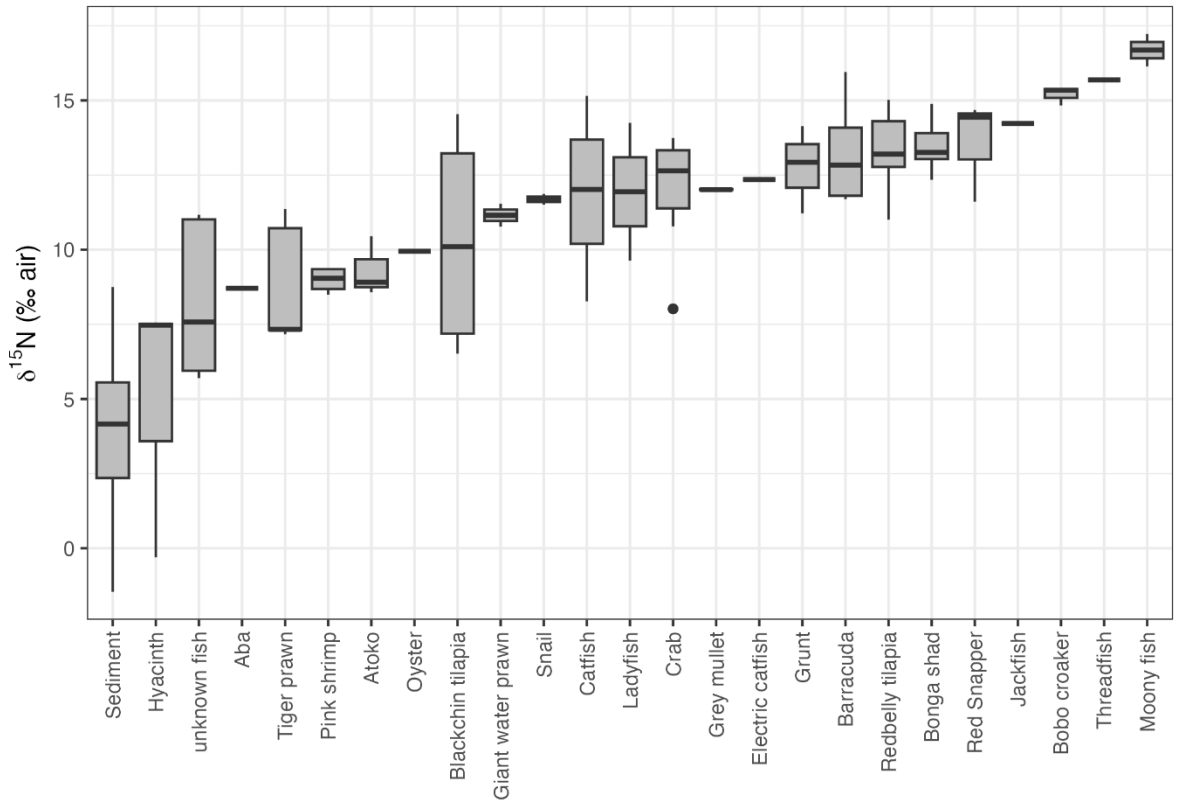


Fig. 2.5: *Box-and-whisker plot distributions of $\delta^{15}N$ among all biota (and sediments for reference) in Lagos lagoon, ordered by mean $\delta^{15}N$. Individual point for crab represents a data outlier.*

The distribution of stable isotope values is explored further in a crossplot of $\delta^{15}N$ versus $\delta^{13}C$ (Fig. 2.6). In such a crossplot, the vertical axis represents primarily trophic level, while the horizontal axis is interpreted to primarily reflect a continuum of carbon sources from more terrestrial/macrophyte sources (lower $\delta^{13}C$) to more marine/microalgal (higher $\delta^{13}C$). Accordingly, macrophytes (water hyacinth) plots at the bottom left of the figure, representing the endmember for primary producer vascular plant biomass. Tiger prawns, blackchin tilapia, aba and unidentified fish collected in the north (Ikorodu) zone plot directly above macrophytes, implying more terrestrial/macrophyte sources of carbon for these primarily herbivorous consumers. Toward the top right of Fig. 2.6 plot the fish barracuda, bobo croaker, grey mullet and jackfish. Higher $\delta^{13}C$ in

these piscivorous consumers implies that they rely on marine sources of carbon. Other biota had intermediate values of $\delta^{13}C$, implying a mixture of terrestrial/vascular and marine/algal sources of carbon. Among these biota, oysters, pink shrimp and atoko fish exhibit the lowest $\delta^{15}N$ reflecting lower trophic positions, while threadfish and moony fish had the highest $\delta^{15}N$ reflecting higher trophic positions. Water snails (*Neritina glabrata*) had unusually high $\delta^{13}C$ values, possibly reflecting dominantly marine or perhaps more benthic sources of carbon.

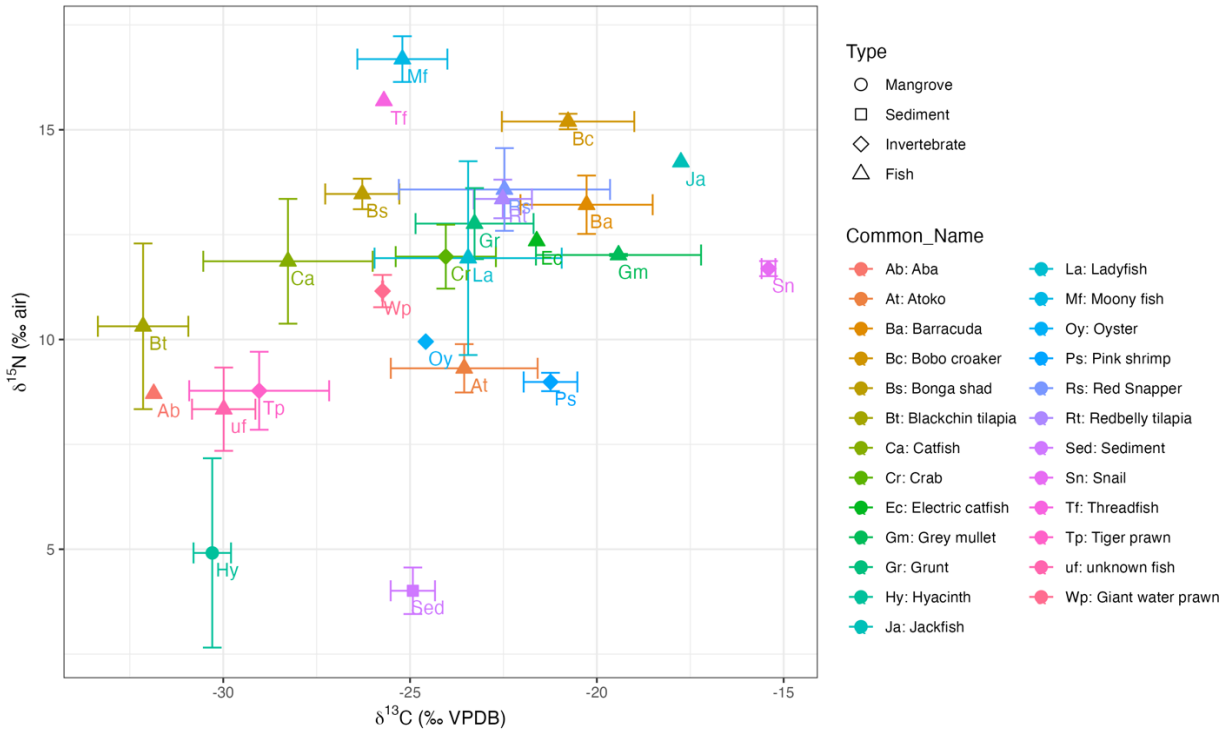


Fig. 2.6: *$\delta^{15}N$ vs $\delta^{13}C$ crossplot of all biota (and sediments) sampled in Lagos lagoon. Individual points represent means; error bars are one standard error.*

2.7.4 Spatial and seasonal variability of stable isotope values of biota

The effects of spatial and temporal variability in biota $\delta^{13}C$ and $\delta^{15}N$ values was tested using three-way ANOVA with trophic guild (see Table 2.3 for guild codes), zone and season as the predictor variables (Table 2.4). For $\delta^{13}C$, zone had the strongest effect (posthoc comparisons: West = South

> East = North; Fig. 2.7a), followed by guild (PP = HC < OC = PC; Fig. 2.7b). Season had a marginally significant effect in the overall model, but it was not significant in the posthoc comparison (Fig. 2.7c). There was a highly significant zone × season interaction likely arising from the unbalanced sampling design. For $\delta^{15}N$, trophic guild had the strongest effect (PP < HC = OC < PC; Fig. 2.7d), followed by zone (West = South = East < North; Fig. 2.8e), and then season (dry < wet; Fig. 2.7f). All two-way interactions on $\delta^{15}N$ were significant, also likely arising from the unbalanced sampling design.

Table 2.4: ANOVA table for the effects of trophic guild, season and zone on each of biota $\delta^{13}C$ and $\delta^{15}N$. Values in bold are significant at the $p < 0.05$ level.

Effect	**df**	**$\delta^{13}C$**		**$\delta^{15}N$**	
		F value	**p**	**F value**	**p**
Trophic Guild	3	8.54	**9.79e-05**	23.76	**$6.16e^{-10}$**
Zone	3	16.20	**1.25e-07**	7.13	**$4.029e^{-4}$**
Season	1	4.37	**0.041**	5.46	**0.023**
Guild × Zone	6	1.41	0.228	2.74	**0.027**
Guild × Season	3	0.80	0.497	5.16	**0.003**
Zone × Season	2	8.57	**0.001**	13.33	**$1.97e^{-5}$**
Guild × Zone × Season	2	1.68	0.195	0.20	0.823

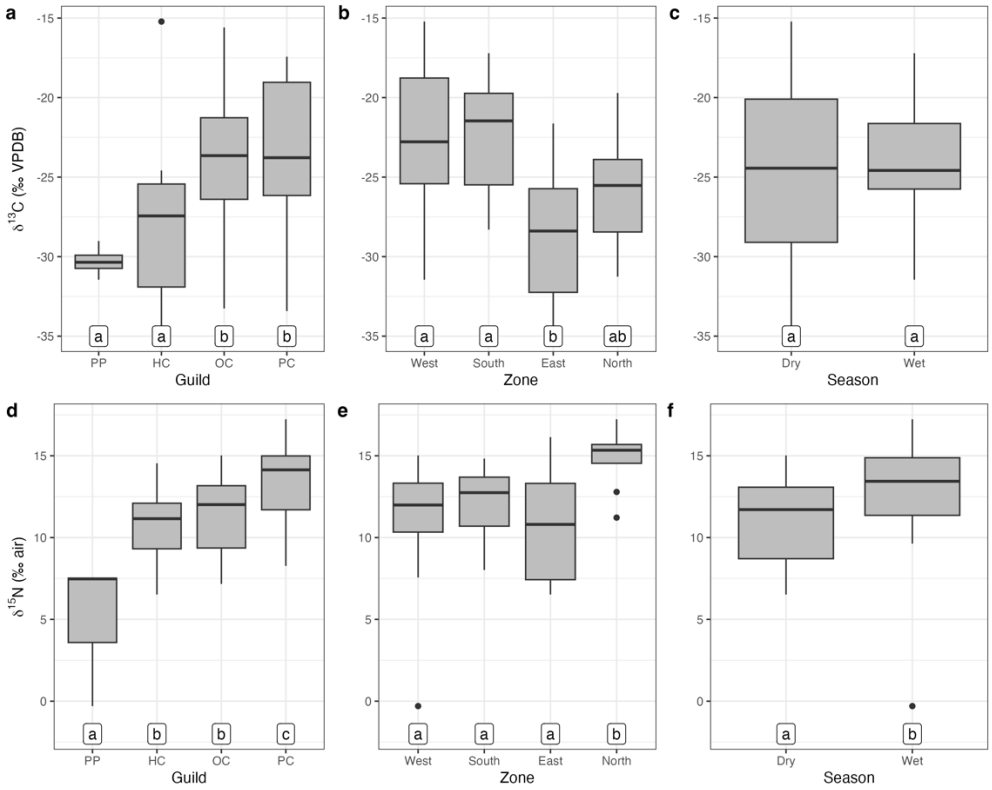


Fig. 2.7: *Boxplots of $\delta^{13}C$ versus trophic guild (a), zone (b) and season (c); and $\delta^{15}N$ versus trophic guild (d), zone (e) and season (f). Letters across the bottom of each graph represent posthoc pairwise comparisons from a 3-way ANOVA (Table 2.4).*

2.7.5 Spatial variability of baseline $\delta^{15}N$

Baseline $\delta^{15}N$ in ecosystems is often measured by analysing the $\delta^{15}N$ of primary producer biomass. In this study, a few samples of floating water hyacinth leaves were collected for the purposes of helping to characterize baseline $\delta^{15}N$. However, sampling logistics prevented collection of the necessary large numbers of primary producer biomass from all four zones. Further, the hyacinth leaves that were collected may have drifted from other areas. Thus, to characterize baseline $\delta^{15}N$, a different approach was taken by plotting $\delta^{15}N$ of all biota and sediments against known trophic position (TP; Fig. 2.8). Biota TP values were obtained mainly from "Fish Base" (fisgbase.org) or "Sea Life Base" (sealifebase.org) data catalogues (see Table 2.3). Sediments were included to increase statistical power and were assigned a TP value of 1.5 to account for mixtures of

autotrophic and microbial heterotrophic biomass that typically comprise sedimentary organic material (LaRowe et al., 2020). Results of linear regressions of $\delta^{15}N$ vs. TP for each zone are presented in Table 2.5. The slopes of the regression equations range from 2.5 ± 0.5 ‰ per trophic level in the west, to 5.23 ± 0.79 ‰ per trophic level in the south. These slopes are close to literature-derived trophic fractionation factors of ~3.4 ‰ (Post, 2002; Zanden & Rasmussen, 2001), thus showing that $\delta^{15}N$ in the samples fractionated predictably with trophic level. We calculated baseline $\delta^{15}N$ by solving the regression equations for a TP of 1. The resulting values were identical, within uncertainty, among the north, east and west zones (mean = 5.2 ± 2.6 ‰; one std. error), and substantially lower (1.6 ±1.3 ‰) in the southern zone.

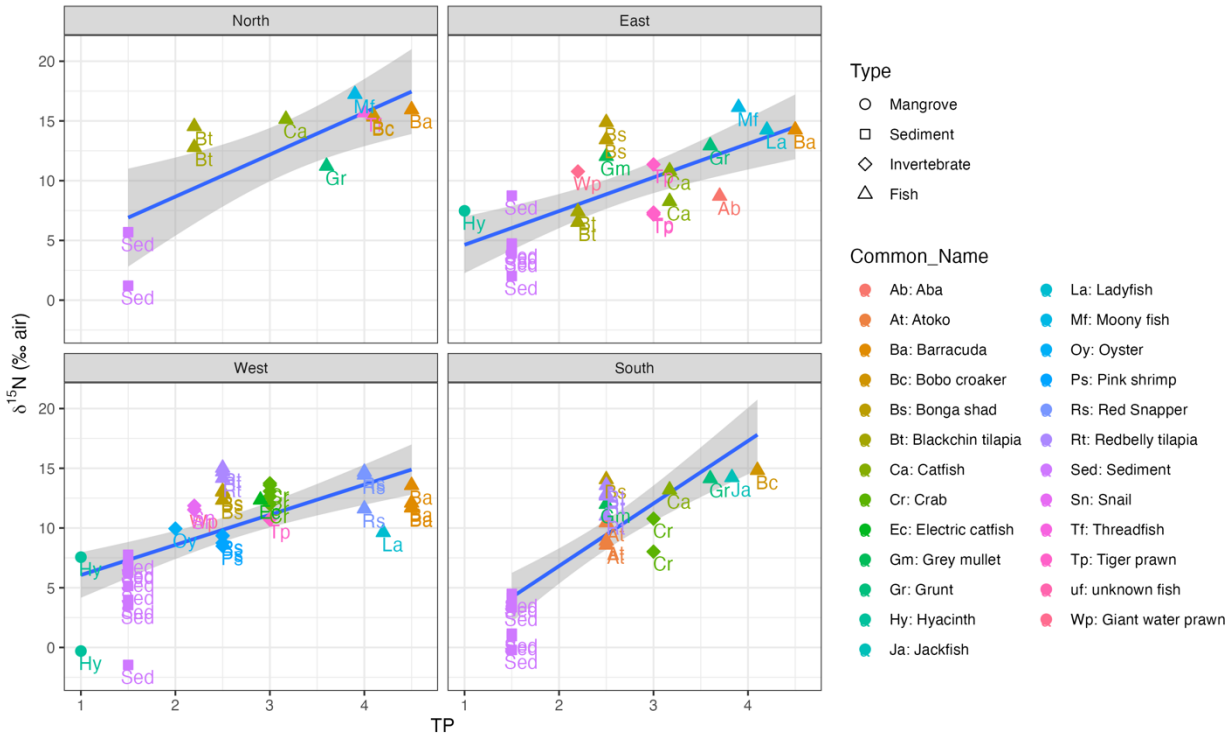


Fig. 2.8: *$\delta^{15}N$ plotted against trophic position (TP) for each zone of the Lagos lagoon, irrespective of season.*

Table 2.5: Linear regression statistics of $\delta^{15}N$ as a function of known trophic position (TP) by zone, irrespective of season, as shown in Fig. 2.7. Sediments were included and assigned a TP value of 1.5. Baseline $\delta^{15}N$ is predicted by solving the regression equations for a TP of 1.0. Uncertainties are reported as ± 1 standard error.

Zone	Slope	Intercept	R^2	p-value	Predicted baseline $\delta^{15}N$
North	3.52 ± 0.92	1.63 ± 3.07	0.58	0.004	5.1 ± 2.2
East	2.82 ± 0.61	1.81 ± 1.70	0.47	$1.42e^{-4}$	4.6 ± 1.1
West	2.52 ± 0.49	3.54 ± 1.38	0.40	$8.73e^{-6}$	6.1 ± 0.9
South	5.23 ± 0.79	-3.65 ± 2.05	0.67	$1.875e^{-6}$	1.6 ±1.3

2.8 Discussion

2.8.1 Environmental Conditions of Surface Water

The environmental conditions of surface water revealed similar temperatures but notable seasonal and spatial variability in salinity (Table 2.1 and Fig. 2.2a). Salinity was moderated by freshwater and seawater. Previous studies had reported similar seasonal and spatial variability and range in values, noting that fluctuation between brackish and freshwater conditions of the lagoon waters (Nkwoji et al., 2020; Nwabueze et al., 2020; Onyema, 2018). The observed variations can be attributed to factors such as rainfall, freshwater inflow, tidal incursion of seawater, and evaporation (Rooney et al., 2018).

2.8.2 Variability of sediment $\delta^{13}C$ and $\delta^{15}N$

This study used stable isotopes analysis to assess spatial variability in carbon and nitrogen sources, as well as evaluate the potential impacts of pollution on food web trophic structure across the urbanization gradient in Lagos lagoon. Spatial variation was observed in both sediment and biota $\delta^{13}C$ and $\delta^{15}N$ values across the lagoon (Figs. 2.2, 2.7a and 2.7e). Although there can be many sources of nitrogen to Lagos lagoon (Fig. 2.9), sediment results (Table 2.2, Fig. 2.2 and 2.3) showed that three major factors drives nitrogen cycling and stable isotope distribution. They include terrestrial, marine and anthropogenic inputs. For $\delta^{13}C$, the variations were stronger and is rather driven primarily by the lagoon's proximity to terrestrial and marine sources than urbanization gradient. Proximity to freshwater and marine input has been shown as a major influencer of carbon distribution in coastal lagoons (Pérez-Ruzafa et al., 2011; Zirino et al., 2014). Freshwater and marine inputs deliver isotopically distinct nutrients and organic matter, which can be traced using stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotope ratios (Asmala et al., 2016; Glibert et al., 2023).

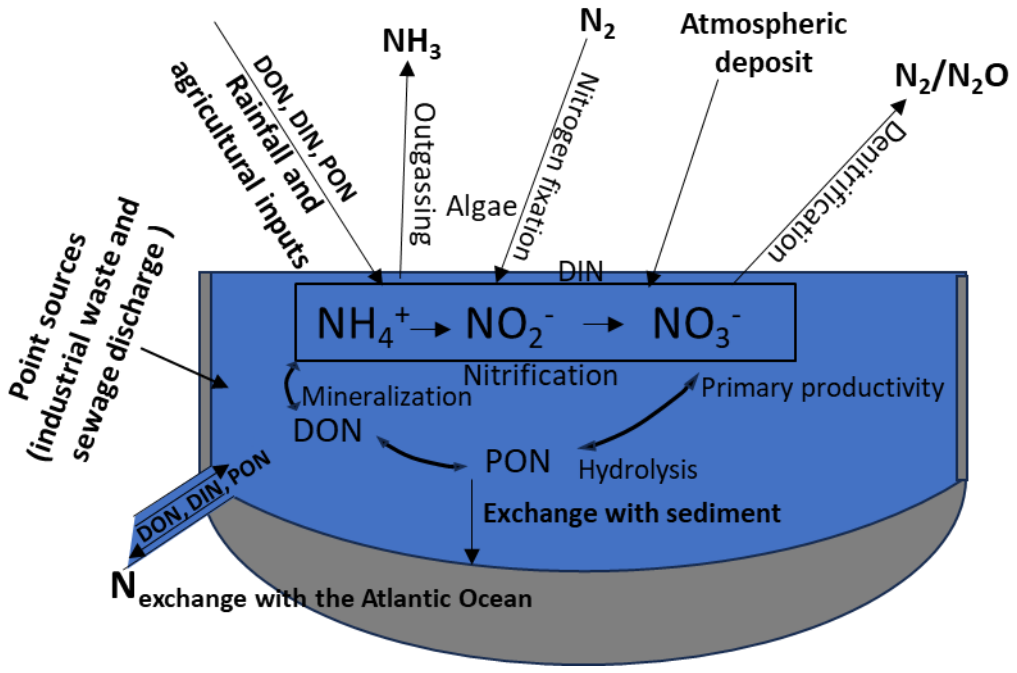


Figure 2.9: *Schematic representation of nitrogen cycling in Lagos lagoon.*

Freshwater inputs typically deliver land-based nutrients and organic matter with more depleted $\delta^{13}C$ values, while marine inputs deliver marine-based nutrients and organic matter with less depleted $\delta^{13}C$ values (Vizzini et al., 2005; Vodička et al., 2019). Consequently, the northern and eastern zones, characterized by high freshwater inputs, showed depleted $\delta^{13}C$ values (< -25 ‰) and elevated C:N ratios, indicating dominance of terrestrial organic matter (Figs. 2.2 and 2.3). Conversely, the southern and western zones, closer to the point of exchange with Atlantic Ocean, exhibited heavier $\delta^{13}C$ values (> -25 ‰) and lower C:N values, suggesting greater marine organic matter influence (González-De Zayas et al., 2020; Graniero et al., 2016). The results of this study agreed with findings from other tropical lagoon ecosystems, such as in New Caledonian lagoon in southwest Pacific Ocean (Briand et al., 2015) and lagoonal estuarine in southeastern Brazil (Barcellos et al., 2005), where terrestrial carbon inputs dominate river-influenced zones, while marine inputs are more prominent in ocean-influenced regions.

Spatial variation in sediment $\delta^{15}N$ values was relatively weak, a pattern often observed in tropical coastal lagoons (Enrich-Prast et al., 2016; Geeraert et al., 2020). The distribution of $\delta^{15}N$ in coastal lagoons tends to be more complex compared to $\delta^{13}C$ due to various factors such as anthropogenic inputs, the mixing of different nitrogen sources (as shown in Fig. 2.4 for Lagos lagoon), and intricate nitrogen cycling processes (Lee et al., 2022). Specifically, $\delta^{15}N$ has been highlighted as a less reliable source indicator in tropical lagoons due to these complexities (Steven Bouillon et al., 2004). However, the western sites near Lagos city exhibited heavier $\delta^{15}N$ values and higher nitrogen loads (higher N content) in sediment samples (Fig. 2.2d and 2.4), reflecting the influence of urbanization and localized nitrogen pollution. Enrichment in $\delta^{15}N$ in coastal water bodies, including tropical lagoons, is commonly linked to urbanization gradients, where differences in nutrient loads drive isotopic enrichment (Nixon et al., 2007; Risk, Lapointe, et al., 2009; Sherwood et al., 2010). These findings align with studies showing that $\delta^{15}N$ reflects urbanization impacts, although its variability in tropical lagoons can be muted by the complex biogeochemical processes at play (Esteves et al., 2008; Geeraert et al., 2020).

2.8.3 Variability of biota $\delta^{13}C$ and $\delta^{15}N$

The biota $\delta^{13}C$ and $\delta^{15}N$ showed terrestrial and marine input including trophic guild as the major drivers of the stable isotope distribution in Lagos lagoon. For $\delta^{13}C$, the wide range of values observed, from -32‰ in blackchin tilapia to -15‰ in water snails (Table 2.3), highlights the diverse carbon sources. The more negative $\delta^{13}C$ values in species like blackchin tilapia suggest a higher reliance on terrestrial or macrophyte-derived carbon (Fig. 2.6), as terrestrial C_3 plants typically exhibit more depleted $\delta^{13}C$ values (S. Bouillon et al., 2008). Conversely, the less negative $\delta^{13}C$ values in species like water snails imply a stronger marine or algal carbon influence. The results generally reflect the variability in carbon sources across the lagoon (Vizzini et al., 2005).

The distribution of $\delta^{15}N$ values follows typical trophic fractionation patterns, where primary producers, such as macrophytes, exhibit the lowest $\delta^{15}N$ values. These values progressively increase with trophic level, from lower consumers like herbivores to higher consumers, including invertebrates and fish, due to isotopic enrichment (Fig. 2.6). This pattern of $\delta^{15}N$ enrichment across trophic levels indicates normal nitrogen assimilation and metabolic processes within the food web (Post, 2002), despite pollution threats in Lagos lagoon. Similar trophic fractionation patterns have been observed in other tropical lagoon systems, such as coastal lagoons in Brazil, where biota exhibit distinct isotopic signatures based on their position in the food chain (Geeraert et al., 2020). Additionally, it has been reported that nitrogen fractionation in tropical lagoons is not obscured by the imprint of major nitrogen sources (Nixon et al., 2007).

The observed $\delta^{13}C$ and $\delta^{15}N$ values suggest that the food web in Lagos lagoon is supported by a mixture of terrestrial and marine-derived carbon, and that nitrogen cycling follows a typical tropical costal marine ecosystem (Fig. 2.6). However, the range of $\delta^{13}C$ values highlights the complex interaction of freshwater and marine inputs expected for a typical tropical coastal lagoon (Vizzini et al., 2005).

2.8.4 Spatial and seasonal variability of stable isotope values of biota

The analysis of spatial and temporal variability in biota $\delta^{13}C$ and $\delta^{15}N$ values using a three-way ANOVA (Table 2.4) provides important insights into how carbon and nitrogen isotopic signatures in Lagos lagoon vary according to different ecological and environmental factors. For $\delta^{13}C$, zone had the strongest effect (Fig. 2.7a), reflecting the influences of terrestrial and marine inputs (Vizzini et al., 2005). Trophic guild also had a strong influence on $\delta^{13}C$ values (Fig. 2.7b), reflecting organisms' diet and trophic fractionation due to metabolic processes (Post, 2002). The

influence of season was marginal (Fig. 2.7c), reflecting a relatively stable carbon inputs over time, despite seasonal fluctuation in environmental conditions such as rainfall (Peterson & Fry, 1987).

The $\delta^{15}N$ values of biota showed that trophic guild was the strongest determinant of variability (Fig. 2.7d), reflecting isotopic fractionation. Isotope fractionation occurs as nitrogen is assimilated and transformed during nitrogen cycling (Fig. 2.9), resulting in an enrichment of approximately 3 ‰ in $\delta^{15}N$ with each step up the food chain (Minagawa & Wada, 1984). This explains the strong influence of trophic guild on $\delta^{15}N$ values. The influence of isotopic fractionation among different trophic levels has been observed in coastal lagoons (Lefebvre et al., 2009; Watson et al., 2020). Higher $\delta^{15}N$ values in piscivores and omnivores reflect their consumption of nitrogen-enriched prey and the higher enrichment at those trophic levels, whereas primary producers display the baseline $\delta^{15}N$ values that represent the foundational nitrogen sources in the ecosystem (Lorrain et al., 2015; Post, 2002).

Geographic zone also influenced $\delta^{15}N$ values, with the northern zone (the area of major river inputs) recording the highest $\delta^{15}N$ values compared to the southern zone (Fig. 2.7e). These results suggest that proximity to terrestrial or marine inputs is a critical factor influencing $\delta^{15}N$ enrichment (Corbisier et al., 2006; Edje et al., 2020; González-De Zayas et al., 2020; Wada, 1991). Unlike $\delta^{13}C$, seasonal variation had a significant effect on $\delta^{15}N$ values (Fig. 2.7f). Higher $\delta^{15}N$ values were observed during the wet season, likely due to increased runoff from terrestrial sources, including sewage and agricultural inputs. These terrestrial nitrogen sources are typically enriched in $\delta^{15}N$, leading to higher values in biota during the wet season (Risk et al., 2009).

These findings support the idea that isotope fractionation, combined with biogeochemical processes and environmental factors like freshwater inputs and runoff, leads to substantial

variation in $\delta^{15}N$ values in biota across coastal lagoons. The observed variability reflects the complex interactions between nutrient sources, trophic dynamics, and local environmental conditions that characterize these ecosystems.

2.8.5 Spatial variability of baseline $\delta^{15}N$

The spatial variability in baseline $\delta^{15}N$ reflects the influence of terrestrial, anthropogenic, and marine inputs, and their complex interaction on the isotopic signature of biota and sediments. It is well-established that the isotopic signatures of organisms reflect the environmental conditions they inhabit (Carter et al., 2019; Potapov et al., 2019). Consequently, the higher and consistent baseline $\delta^{15}N$ values, with a mean of 5.2 ± 2.6 ‰ in the northern, eastern, and western zones (Fig. 2.8), suggest that organisms in these areas primarily rely on terrestrial and urban nitrogen sources. In contrast, the southern zone of the lagoon exhibited a substantially lower baseline $\delta^{15}N$ value (mean = 1.6 ± 1.3 ‰), indicating a different nitrogen dynamic. This suggests greater influence of marine nitrogen sources, meaning that organisms in this zone primarily rely on and reflect marine nutrient inputs. Marine sources typically have lower $\delta^{15}N$ values compared to terrestrial and anthropogenic inputs (Post, 2002), supporting the spatial pattern of variability in $\delta^{15}N$ signatures observed in this study. The observed variability in baseline $\delta^{15}N$ is consistent with patterns seen in other coastal systems, where terrestrial, anthropogenic, and marine inputs have been shown to affect $\delta^{15}N$ values (Bouillon et al., 2008; Vizzini et al., 2005). This suggests that the isotopic signatures of nitrogen in Lagos lagoon are strongly influenced by the differences between terrestrial vs marine sources of carbon.

2.8.6 Impacts of pollution on Lagos lagoon

Despite the significant anthropogenic influence resulting from high population density and inadequate waste management in Lagos city, the sediment and biota isotope results failed to detect

any obvious impact of anthropogenic activities. This conclusion is supported by two key findings. First, the lagoon exhibits a relatively typical trophic structure, with predictable enrichment in $\delta^{15}N$ (+2.8 to 5.2 ‰ per trophic level) and $\delta^{13}C$ values, following the expected trophic fractionation from primary producers through to piscivorous consumers (Figs. 2.5 and 2.6). Eutrophication has been shown to disrupt trophic interactions, often leading to deviations from the typical trophic structure (Graniero et al., 2016; Lefebvre et al., 2009; van der Lee et al., 2021). Therefore, the observation of a typical trophic structure in Lagos lagoon may be evidence of low pollution impacts, suggesting that anthropogenic activities have not significantly altered the natural food web dynamics.

Also, the $\delta^{15}N$ values in both sediment (Fig. 2.2) and biota (Table 2.3) samples did not reach the elevated levels typically associated with significant sewage-derived nitrogen inputs (Nixon et al., 2007; Risk et al., 2009). Normally, sewage wastewater exhibits $\delta^{15}N$ enrichment ranging from +10 to +20 ‰ (Kendall, 1998b), due to nitrogen transformations such as ammonia volatilization, denitrification, and nitrification of ammonia (Leigh et al., 2019; Risk et al., 2009). In many coastal environments, elevated $\delta^{15}N$ values have been directly linked to increased sewage discharge driven by population growth (González-De Zayas et al., 2020; Risk, et al., 2009; Risk et al., 2009). Baseline $\delta^{15}N$ values evident in this (Fig. 2.2), did not reach levels typically indicative of major pollution.

The absence of pronounced $\delta^{15}N$ enrichment in this study could be attributed to several mitigating factors: (1) the lagoon's shallow depth and short water residence time (approximately 24 days; (Alademomi, 2017), which likely prevent nutrient accumulation and prolonged cycling—this contrasts with systems like Chesapeake Bay, where longer water residence times lead to more pronounced $\delta^{15}N$ enrichment in nitrogen-impacted areas (Oczkowski et al., 2008); (2) the

predominance of ammonium and nitrate as nitrogen species, which may result in lower $\delta^{15}N$ values in primary producers; and (3) the relatively low $\delta^{15}N$ values of untreated sewage in Lagos, which may not lead to the isotopic enrichment typically observed in more heavily impacted environments (Costanzo et al., 2001; Savage, 2005).

Together, these factors mitigate the impact of anthropogenic nitrogen inputs, preventing the lagoon from exhibiting the high $\delta^{15}N$ values often associated with pollution in urban coastal systems. This suggests that the method employed here were unable to unambiguously detect anthropogenic impacts to the lagoon. Continued monitoring should be used to manage and mitigate water quality issues in Lagos lagoon and to prevent future degradation of the lagoon's ecological health.

2.9 Conclusions

Stable isotopes of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) were utilized to explore the seasonal and spatial variability in nutrient inputs and their impacts on the food web trophic structure of Lagos lagoon, which is located within an area experiencing rapid population growth and lacking adequate wastewater management (Ike et al., 2018; Omololu & Lawal, 2013). We sampled biota and sediment from four zones representing both highly urbanized and less urbanized areas of the lagoon, and subsequently analyzed for $\delta^{13}C$ and $\delta^{15}N$ values.

The $\delta^{13}C$ values in both biota and sediments exhibited strong spatial variability, with lighter $\delta^{13}C$ values observed in freshwater-influenced zones and heavier $\delta^{13}C$ values in marine-influenced zones, indicating that terrestrial and marine sources of carbon are the primary drivers of $\delta^{13}C$ distribution across the lagoon.

$\delta^{15}N$ variability in both sediments and biota reflected trophic fractionation, with $\delta^{15}N$ values increasing predictably with known or inferred trophic positions. The calculated baseline $\delta^{15}N$ values showed that the northern, eastern, and western zones had higher baseline $\delta^{15}N$ values compared to the southern zone, which exhibited lower baseline $\delta^{15}N$ values. However, these baseline values were within the range of natural seawater nitrate and terrestrial soil nitrate, making it difficult to attribute specific nitrogen cycling changes solely to anthropogenic inputs.

We observed heavier $\delta^{15}N$ values in both sediment and biota from the highly urbanized zones, suggesting that anthropogenic inputs, including sewage and urban runoff, contribute to nitrogen variability in the lagoon. Despite this, the overall effect of seasonality on $\delta^{13}C$ and $\delta^{15}N$ values was marginal compared to the more pronounced spatial and trophic effects.

This study marks the first isotope study in Lagos lagoon and presents the first integrated measurement (in time and space) of nutrients within the lagoon. As an exploratory study, it served as a temporal baseline and paves the way for a more robust study and can serve as a baseline for future pollution monitoring programs.

2.10 Future work

Future research should focus on increasing the spatial resolution of the study by adding more sampling sites within each zone of Lagos Lagoon. This will allow for a more detailed understanding of local variations and better identification of specific nutrient input sources. Additionally, expanding the scope of biota sampling to include a broader range of trophic levels will provide a more comprehensive view of food web structure and trophic dynamics in the lagoon.

To further enhance our understanding of nutrient inputs, it is essential to determine the isotopic signatures of specific pollution sources such as river and ocean inputs. This will enable the identification and quantification of their respective contributions to nutrient loading in the lagoon and facilitate more effective monitoring and management strategies.

Our findings suggest that terrestrial and marine inputs, along with anthropogenic influences, are key drivers of nutrient variability in Lagos lagoon. Therefore, future studies should focus on understanding the mixing dynamics between these sources and their effects on stable isotope distributions. This could involve characterizing water circulation patterns and flushing times to better interpret spatial and seasonal variations, including how these factors interact to influence isotopic signatures and their relationship to pollution impacts.

Chapter 3

Comparison of Nutrient Analyses of Water Samples Between Labs and Lessons Learned

3.1 Preface

This chapter is based on a pilot study of nutrient levels in Lagos lagoon and will inform enhancement of the effectiveness of international collaboration in this area of environmental science research, especially with developing countries. The study design and sampling plans were designed and led by me, assisted by our collaborators from NIOMR and University of Lagos. Our early experience included in this chapter was presented at the AGU Ocean Science Meeting 2024 in New Orleans, USA as an oral presentation.

3.2 Abstract

Accurate measurement of nutrient levels is crucial for assessing water quality, eutrophication, and understanding ecosystem dynamics. In Lagos lagoon, existing measurements show apparent inconsistencies with reported concentrations spanning up to three orders of magnitude. While real variability and variations in analytical methods contribute to these discrepancies, a sizable portion may be attributed to uncertainties during data workup and reporting. In this pilot study, we conducted comparative analyses of nutrient levels in water samples between laboratories in Nigeria (Unilag lab) and Canada (CERC-Ocean lab), using exchange of water samples from both Lagos lagoon and Bedford Basin, as well as reference materials. Our findings revealed some similarities in nutrient distribution patterns but significant differences in nutrient concentrations between the laboratories, with the Unilag lab consistently showing lower concentrations compared to the CERC-Ocean lab. We identified several challenges encountered during the study, including issues related to analytical methods, data workup, and logistical constraints associated with sampling and sample transfer. Based on these observations, we make several recommendations to improve future studies. Notably, the seasonality and spatial distribution of nutrients in Lagos lagoon, as analyzed by the Unilag lab, were consistent with our stable isotope results, despite the considerable discrepancies observed in the inter-laboratory comparison of concentrations.

3.3 Introduction/Background

Coastal lagoons represent unique and fragile ecosystems, offering vital ecological services such as sources, food, transportation, recreation, and supporting diverse communities of flora and fauna (Grillo & Venora, 2012; Vasconcelos et al., 2011). Among these, Lagos lagoon stands as a key example, located within a region experiencing rapid urbanization and population growth. As human activities expand along its shores, concerns over the health and sustainability of this critical ecosystem have heightened over the years (Fajemila et al., 2020; Nkwoji et al., 2020).

Central to these concerns are nutrient levels within the lagoon waters, a parameter of importance for understanding the ecosystem dynamics (Acquavita et al., 2015; Pitacco et al., 2019; Vijay et al., 2021), assessing water quality and eutrophication (Leigh et al., 2019; McLaughlin, 2014), and for safeguarding both the health of the water and humans that depend on the lagoon (Sandifer & Sutton-Grier, 2014).

Numerous studies have been directed towards measuring and understanding the lagoon's water quality by quantifying nutrient levels amidst the burgeoning population and escalating pressures on Lagos lagoon, (e.g., Akagha et al., 2020; Fasuyi et al., 2021; Temitope Emmanuel, 2021). However, according to our review, these endeavors encounter multifaceted challenges that may hinder the accuracy, reliability and hence interpretation of measurement. Such challenges are common to nutrient analyses generally and could arise during different steps in analyses including sample collection, transfer, analyses, data workup and reporting (Karthikeyan et al., 2009; McGrath et al., 2019a).

Table 3.1 presents a summary of previous nutrient measurements from the Lagos lagoon as reported in the literature. The reported levels span up to three orders of magnitude in concentration

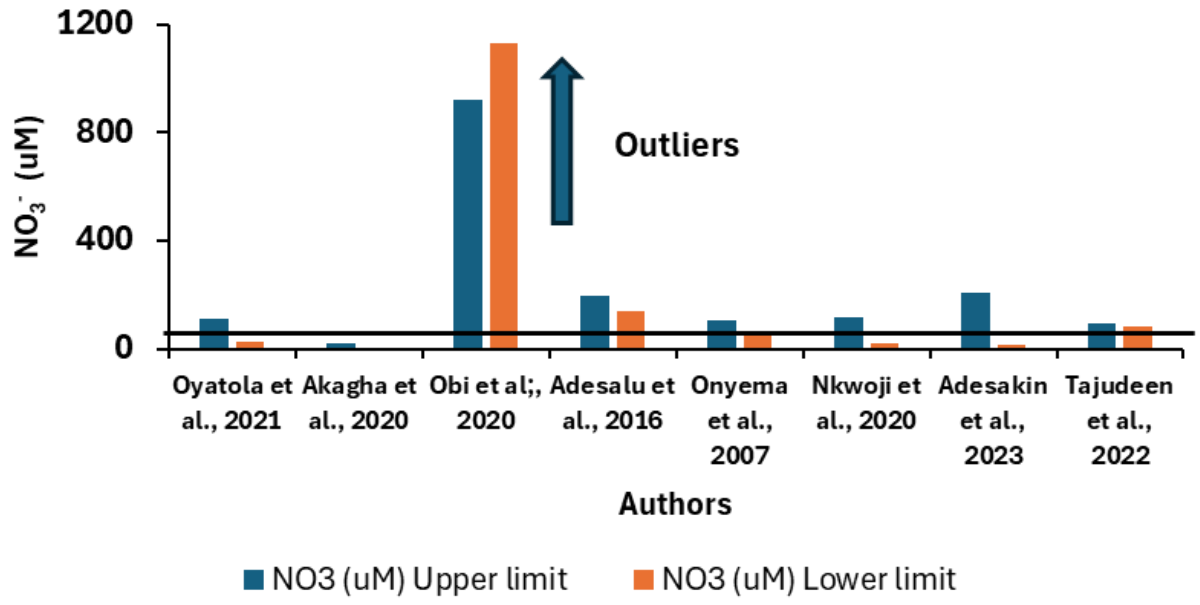
(Figs. 3.1). While some variations could be real or attributed to differences in analytical methods (Karthikeyan et al., 2009; McGrath et al., 2019), a substantial portion may also arise from data workup including, even, uncertainty of the units used for results expression. The conventional measurement unit adopted for nutrients by marine chemists is now either µM (molarity) or µmol kg-sw^{-1} (molinity). The molinity is preferred for open ocean measurements to account for effects of ambient pressure and temperature of seawater on density and is calculated knowing the salinity of the sample and the temperature of the laboratory when the analysis is conducted. The mg L^{-1} unit is commonly used in aquatic sciences but no longer utilized by the oceanographic community, in part due to the potential risk of confusion, which may arise from expressing either in mg L^{-1} of the element (N-NO_3^-) or in mg L^{-1} of the ion (NO_3^-) (Daniel et al., 2020). The risk of inconsistency or lack of clarity in the use of units not only impedes data interpretation but also hinders efforts to compare results across studies and discern long-term trends in nutrient levels.

Moreover, a notable gap exists in information regarding the methods, standards, and utilization of any reference standards for nutrient determination, further complicating the interpretation and comparison of measurement results. Use of certified reference materials (CRMs) has been identified as a crucial step toward improving the intercomparison of dissolved nutrient results in seawater samples (Michio et al., 2016). Integrating standardized reference materials into nutrient analyses protocols can enhance the reliability and robustness of measurements, enabling more accurate assessment of nutrient dynamics and facilitating meaningful comparisons between different datasets. However, these reference materials can be expensive.

Considering these challenges, it becomes imperative to delve deeper into the details of nutrient measurement procedures used in Lagos lagoon. In accordance, we embarked on a Canada-Nigeria pilot study to assess the inter-comparability of water quality parameters, particularly nutrient

Table 3.1. Ranges in literature reported nutrient levels in Lagos lagoon.

Nutrient (unit)	Reported range	Converted (µM)	Author(s)
NO_3^- (mg L^{-1})	1.77 - 6.98	28.55 - 112.58	(Oyatola et al., 2021)
PO_4^{3-} (mg L^{-1})	8.68 - 8.94	91.37 - 199.37	
NO_3^- (µM)	1.45 - 20.16	1.45 - 20.16	(Akagha, Nwankwo, et al., 2020)
PO_4^{3-} (µM)	0.18 - 18.76	0.18 - 18.76	
NO_3^- (mg L^{-1})	57.20 - 70	922.58 - 1129.03	(Obi et al., 2016)
PO_4^{3-} (mg L^{-1})	0.40 - 1.62	4.21 - 17.05	
NO_3^- (mg L^{-1})	8.80 - 12.10	141.94 - 195.16	(Adesalu et al., 2010)
PO_4^{3-} (mg L^{-1})	2.20 - 12.5	23.16 - 131.58	
NO_3^- (mg L^{-1})	3.05 - 6.82	49.19 - 105.16	(Onyema, 2007)
PO_4^{3-} (mg L^{-1})	0.48 - 0.97	5.05 - 10.21	
NO_3^- (mg L^{-1})	1.20 - 9.20	19.36 - 118.38	(Nkwoji et al., 2020)
PO_4^{3-} (mg L^{-1})	0.30 - 1.70	3.16 - 17.90	
NO_3^- (mg L^{-1})	0.98 – 13.01	15.81 – 209.84	(Adesakin et al., 2023)
PO_4^{3-} (mg L^{-1})	0.97 – 301.00	10.21 – 72.53	
NO_3^- (mg L^{-1})	5.03 – 5.79	81.13 – 93.39	(Tajudeen et al., 2022)
PO_4^{3-} (mg L^{-1})	20.02 - 20.04	210.74 – 210.95	



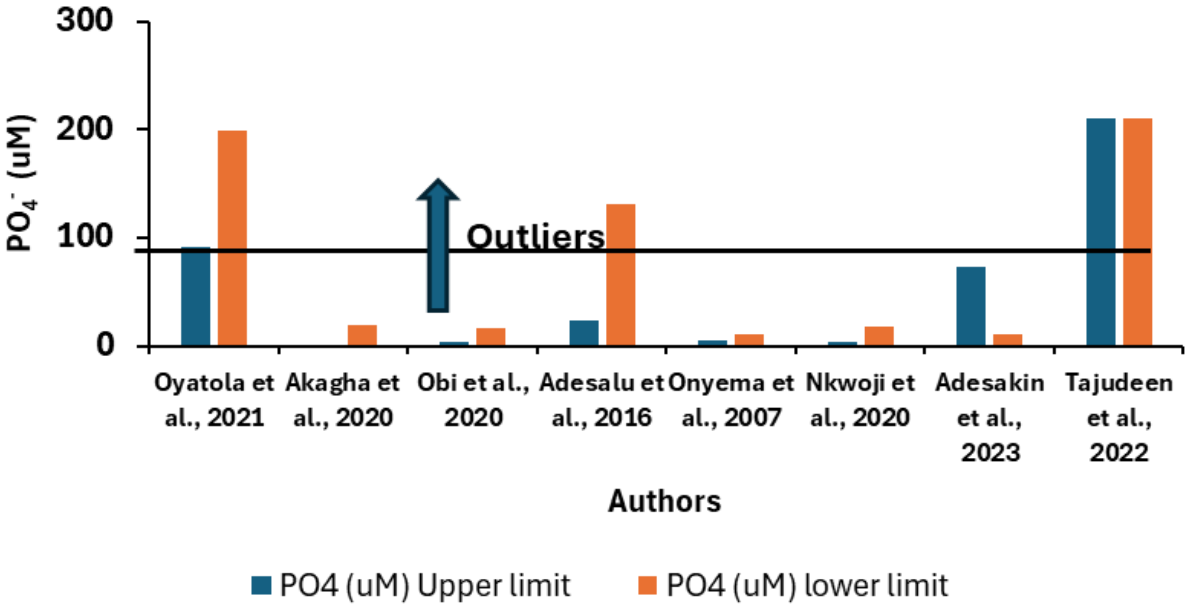


Figure 3.1: *The reported range in nutrient levels in Lagos lagoon as reported in the literature but converted to µM of* NO_3^-.

concentrations, in Lagos lagoons, Nigeria. By conducting a comparative analysis of nutrient analyses between laboratories in Canada and Nigeria, this study sought to evaluate the quality and consistency of nutrient measurement practices. In doing so, we not only would bolster our understanding of environmental dynamics but also pave the way for informed decision-making and effective management strategies.

The Canada-Nigeria collaboration emerged from a recognition of the significant disparities in ocean research, technological capabilities and funding between the two nations, coupled with a shared interest in advancing the blue economy. Canada stands out as a global leader in ocean research, ocean literacy, and technological innovation, as evidenced by numerous studies (Cavas et al., 2023; Potter & Pearson, 2023). In contrast, Nigeria, along with several other African countries, faces challenges in technology adoption, maintenance and sustainable development (Oghuvbu et al., 2022). These disparities pose obstacles to the advancement of research including the implementation of effective nutrient monitoring strategies within the Lagos lagoon and other coastal ecosystems in Nigeria.

Canada and Nigeria share the Atlantic Ocean as a border and have a common goal of promoting sustainable marine ecosystems. This shared mandate underscores the potential for collaboration between the two nations to serve as a catalyst for advancing research and development in Nigeria and the broader West African region, while simultaneously fostering the sustainability of ocean resources. By leveraging Canada's capacity in ocean research and technology alongside Nigeria's unique insights and local knowledge, such collaboration has the potential to drive significant progress in addressing environmental challenges and promoting the sustainable management of marine ecosystems.

The challenges facing international scientific cooperation are however multifaceted and encompass financial, logistical, analytical, and institutional barriers (Pischke et al., 2017; Yao, 2021). These challenges are particularly pronounced in the context of environmental research, where diverse stakeholders, methodologies, and regulatory frameworks intersect (Pischke et al., 2017). However, overcoming these challenges is imperative for advancing scientific knowledge, informing evidence-based policymaking, and promoting sustainable development globally.

Therefore, this technical report not only endeavors to contribute insights into the nutrient dynamics of Lagos lagoon but also aims to shed light on the complexities and challenges of international collaboration in environmental research. By identifying key challenges and making recommendations based on lessons learned, we seek to improve international collaboration while also improving the understanding of the nutrient levels in Lagos lagoon. This will help in the establishment of future, more robust monitoring programs for lagoon ecosystems and fostering stronger of partnerships between researchers, institutions, and governments across borders.

3.4 Objectives and Strategies

The objectives of this chapter include:

1. To compare results of between lab nutrient analyses of water samples
2. To evaluate spatial variation and seasonality in nutrient distribution in Lagoa lagoon
3. To identify key challenges facing international collaboration in environmental research and propose possible solutions.

To meet objective number 1, water samples from Lagos lagoon and Bedford Basin, along with international reference materials used in the CERC-ocean lab, were exchanged between the Unilag

and Dalhousie CERC-ocean laboratories. Subsequently, both laboratories conducted analyses on the samples and reference materials for comparison.

3.5 Methods

In this pilot study, along with our partnering institutions, the National Institute of Oceanography and Marine Research (NIOMR) and the University of Lagos (Unilag), we embarked on sampling expeditions in Lagos lagoon. We collected water samples during dry (December 2022) and wet (August 2023) seasons. The lagoon was divided into four zones, northern (Ikorodu), southern (Apapa), western (Makoko), and eastern (Epe) parts (Fig. 3.2). For the dry season, we sampled 10 stations, while in the wet season, we sampled 12 stations from these zones. The number of stations was not evenly distributed among the zones. Some zones had only a single station while others had up to four (Table 3.2). The zones were chosen to reflect both highly populated and less populated areas of the lagoon. Additionally, the allocation of stations was influenced by logistical considerations, such as boat time. For instance, the northern zone, being the last zone sampled, was limited to only one station due to constraints on boat time. The sampling plans and choice of zones were made in consultation with our collaborators, who provided valuable recommendations to enhance the effectiveness and scope of the study.

Water samples were directly collected from the lagoon surface using a sampling syringe, filtered through a surfactant-free cellulose acetate with 0.45 μm pore prefilter (SFCA-PF) into plastic sampling vials. This was done in triplicate for independent nutrient analyses at laboratories in Canada and Nigeria. Nutrient analyses were carried out at both the University of Lagos (Unilag) and Dalhousie University (CERC-Ocean). At NIOMR, a portion of the water samples were stored in a dry shipper containing liquid nitrogen and shipped to Dalhousie University, Canada for nutrient analyses.

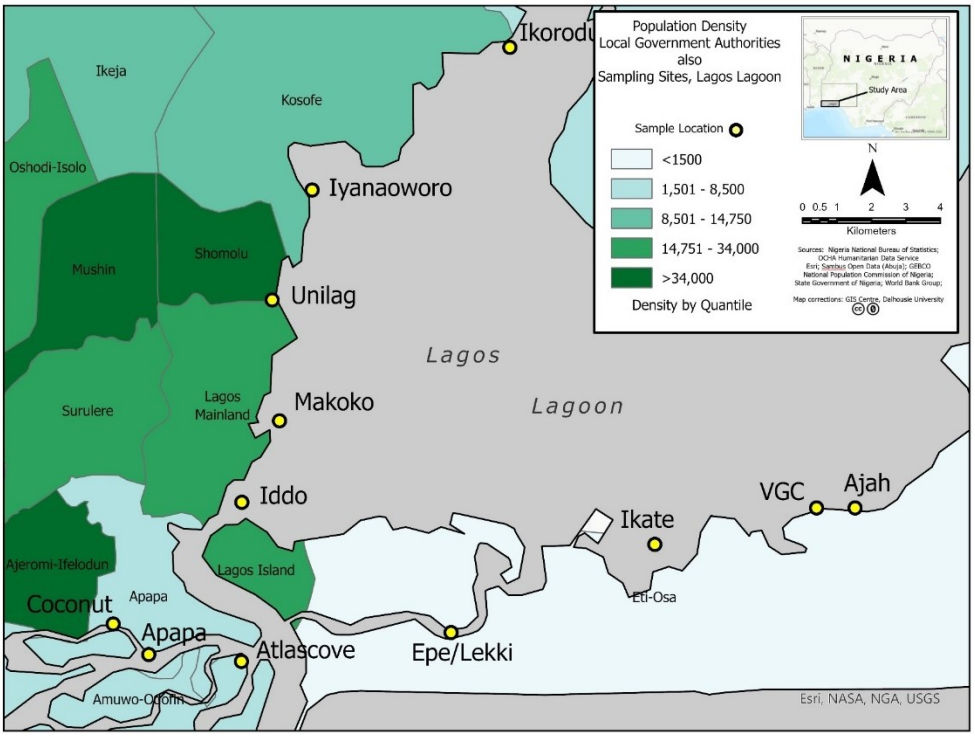


Figure 3.2: *Map of Lagos lagoon showing the sampling sites.*

Table 3.2: Summary of sampling efforts in the Lagos lagoon.

Zone	Station	Location		Season sampled
		Longitude	Latitude	
North	Ikorodu	06°59'N	03°46'E	Dry/Wet
South	Apapa	06°43'N	03°37'E	Dry/Wet
	Coconut	06°44'N	03°36'E	Dry/Wet
	Atlas Cove	06°43'N	03°39'E	Dry/Wet
East	Ajah	06°47'N	03°55'E	Dry/Wet
	Ikate	06°43'N	03°50'E	Wet
	Epe/Lekki	06°44'N	03°45'E	Dry/Wet
	VGC	06°47'N	03°54'E	Wet
West	Iddo	06°47'N	03°38'E	Dry/Wet
	Makoko	06°49'N	03°38'E	Dry/Wet
	Unilag	06°52'N	03°40'E	Dry/Wet
	Oworo	06°60'N	03°41'E	Dry/Wet

Additionally, another set of samples collected from Bedford Basin and filtered through SFCA filter was shipped to the lab in University of Lagos for analyses. These samples were also analyzed at the CERC-ocean lab in Dalhousie University.

3.5.1 Sample preparations and laboratory analyses

Two labs were involved in this comparative nutrient analyses. The methods of analyses are reported according to the different labs.

Laboratory analyses (UNILAG)

Analyses of the water samples at Unilag were carried out in the Environmental Chemistry Laboratory of the Department of Chemistry, University of Lagos. At the laboratory, water samples were stored in a freezer at -20° C for a day before analyses. However, due to intermittent power outages, freezer temperatures could have been higher. Samples from all stations and both seasons were analysed for NO_3^-, and PO_4^{3-}.

Total phosphate was determined on a UV-visible spectrophotometer as orthophosphate at 880 nm using the molybdenum blue method (APHA WEF, 2012). 2.5 M sulfuric acid solution was prepared and 1.3715 g potassium antimonyl tartarate (PAT) was dissolved in 500 mL of ultrapure water. 20 g ammonium molybdate was dissolved in 500 mL ultrapure water while 1.76 g of ascorbic acid was dissolved in 100 mL ultrapure water. These reagents were prepared for the purpose of colour development. Stock phosphate solution (50 mg PO_4^{3-}-P L^{-1}) was prepared using potassium dihydrogen orthophosphate from which five working standards with a concentration range of 0.4–2.0 mg PO_4^{3-}-P L^{-1} including a blank of ultra-pure water, were used to generate the calibration curves for the analyses. The coloured reagent was mixed in the following proportions for 100 mL of the above reagents: 50 mL 2.5 M H_2SO_4, 5 mL PAT solution, 15 mL ammonium molybdate

solution, and 30 mL ascorbic acid solution. 8 mL of the coloured reagent was added to 50 mL of each sample, allowed to stand for 10 minutes and measured spectrophotometrically.

Nitrate was determined using the Griess reaction method described as follows: aliquots of each sample were transferred into separate 50 mL volumetric flasks and diluted with 20 mL deionized water. The solution was shaken on a reciprocating shaker for 5 minutes. 0.1 g of Zinc powder, followed by 1 mL of hydrochloric acid solution were then added and the mixture allowed to stand for 10 minutes (to reduce nitrate to nitrite). Afterwards, 2.5 mL of sulfanilic acid solution was added, shaken until homogeneously mixed and left to stand for 5 minutes. N-(1-Naphthyl) ethylenediamine dihydrochloride solution (2.5 mL) was then added and the mixture brought to mark with deionized water. The absorbance of the solution was measured at 540 nm. Standard solutions of 0.1 – 2.0 mg L^{-1} of NO_3^- (25 mL each) prepared from freshly dried $NaNO_3$ were similarly treated. The concentration of total nitrite (nitrite and converted nitrate) was calculated using the regression equation from the calibration curve obtained and the dilution factor. The concentration of converted nitrate (nitrate that has been converted to nitrite) was obtained by subtracting the concentration of nitrite from the total nitrite obtained for each sample.

Laboratory analyses (Dalhousie University)

The analyses were carried out in the Canada Excellence Research Chair in Ocean Science and Technology (CERC-ocean) lab, Dalhousie University. Upon arrival, the samples were removed from the dry shipper and stored in a freezer (-20° C) for eight months prior to nutrient analyses. Nitrate (NO_3^-) and phosphate (PO_4^{3-}) were analyzed using a Skalar San^{++} Continuous Flow Analyzer, according to method described by McGrath et al. (2019). The analyser ran four channels of nutrients simultaneously: total oxidised nitrogen, nitrite, silicate, and phosphate. Through an auto-sampler, sample was drawn into the analyser with the aid of a needle and was further

distributed into the four channels. Each channel had its own set of reagents. The stream of reagents and samples was pumped through the manifold to undergo treatment such as mixing and heating before entering a flow cell for detection. The air-segmented flow promotes mixing of sample and prevents crossover between samples. The reaction of the reagents develops a colour, which is measured as an absorbance through a flow cell at a given wavelength. The Skalar Interface ensures all data are transmitted to the Skalar Flow Access software.

It is important to note that all the dry season water samples from Lagos lagoon were broken during transit from Lagos to Halifax and were therefore not analyzed. The wet season samples from Lagos lagoon thawed during shipment to Halifax and the Bedford Basin samples thawed during shipping to Lagos. Customs held the samples for two weeks, which prolonged the transit time. However, despite serious reservations about sample quality, we proceeded with the comparative nutrient analyses as a first step toward improving international collaboration in environmental research and nutrient measurement in aquatic ecosystems. The comparative analyses were based primarily on the wet season samples and on samples from the Bedford Basin.

Reference materials

The reference material used for the nutrient analyses in each laboratory was KANSO-CRMs: RMNS. It is stabilized for a long time under room temperature storage, making it ideal for nutrient analyses results for a variety of environmental conditions.

3.6 Results

The results section is divided into two:

1. **Inter-laboratory nutrient comparison**: This section will focus on comparing nutrient results between the Unilag laboratory and the CERC-Ocean laboratory for the different samples.
2. **Unilag nutrient analyses**: This section will present the results of nutrient analyses conducted solely at the Unilag laboratory, examining both seasonal and spatial distributions. The purpose of this phase is to relate the trends in results to the isotope data presented in Chapter Two of this thesis.

3.6.1 Inter-laboratory nutrient comparison

3.6.1.1 Comparison of the reference materials

The reference material nutrient results were similar for both Unilag and CERC-Ocean laboratories despite the differences in analytical methods. However, Unilag results tended to show slightly higher values compared to CERC-Ocean results (see Table 3). Phosphate concentration was 1.16 ± 0.01 µM and 1.17 ± 0.02 µM, while the NO_3^- concentration was 16.39 ± 0.01 µM and 16.94 ± 0.01 µM for CERC-ocean laboratory and Unilag laboratory respectively. The NO_3^-:PO_4^{3-} ratios were therefore 14:1 and 15:1 for CERC-ocean and Unilag laboratories, respectively.

Table 3.3: Nutrient concentration of KANSO CRMs measured at University of Lagos and Dalhousie University CERC-ocean laboratory.

Laboratory	**PO_4^{3-}**	**NO_3^-**	**NO_3^- / PO_4^{3-}**
	µM		
	n = 3		
Unilag	1.17±0.02	16.94±0.01	15:1
CERC-ocean	1.16±0.01	16.39±0.01	14:1
Standard values	1.20	17.36	15:1

3.6.1.2 Between lab comparison of Bedford Basin results

Generally, in terms of nutrient levels, CERC-Ocean lab results were significantly and considerably higher compared to the Unilag lab's results (Fig. 3.3). The CERC-Ocean lab measurements were consistent with data collected from the Bedford Basin Time-Series (Haas et al., 2021). However, both sets of results followed a similar pattern, with nutrient levels increasing with depth (Table 6c). For the CERC-Ocean lab, the PO_4^{3-} concentration ranged from 0.90 ± 0.03 μM to 5.85 ± 0.14 μM, while the NO_3^- concentration ranged from 8.74 ± 0.16 μM to 22.55 ± 0.18 μM. The NO_3^-:PO_4^{3-} ratio therefore ranged from 4:1 to 10:1. For the Unilag lab, the PO_4^{3-} concentration ranging from 0.01 ± 0.00 μM to 0.23 ± 0.04 μM, and NO_3^- from 0.67 ± 0.13 μM to 1.60 ± 0.53 μM (Fig. 3.3). The NO_3^-:PO_4^{3-} ratio ranged from 4:1 to 84:1.

3.6.1.3 Between lab comparison of Lagos lagoon results

CERC-Ocean laboratory results were also, overall, significantly higher compared to Unilag laboratory results for the Lagos lagoon samples, although the reliability of the samples analyzed at Dalhousie is called into question as the samples were thawed during transit. Again, the two sets of results were similar in terms of the general pattern of distribution. The PO_4^{3-} concentration for the zones ranged from 0.18 ± 0.00 μM to 3.75 ± 0.01 μM and 0.22 ± 0.01 μM to 0.60 ± 0.01 μM, while the NO_3^- concentration for the zones ranged from 8.37 ± 0.04 to 23.22 ± 0.00 μM and 7.26 ± 0.02 to 8.39 ± 0.02 μM for the CERC-Ocean laboratory and Unilag laboratory analyses, respectively (Fig. 3.5). The NO_3^-:PO_4^{3-} ratio ranged from 3:1 to 129:1 and 12:1 to 34:1 for the CERC-Ocean laboratory and Unilag laboratory results, respectively.

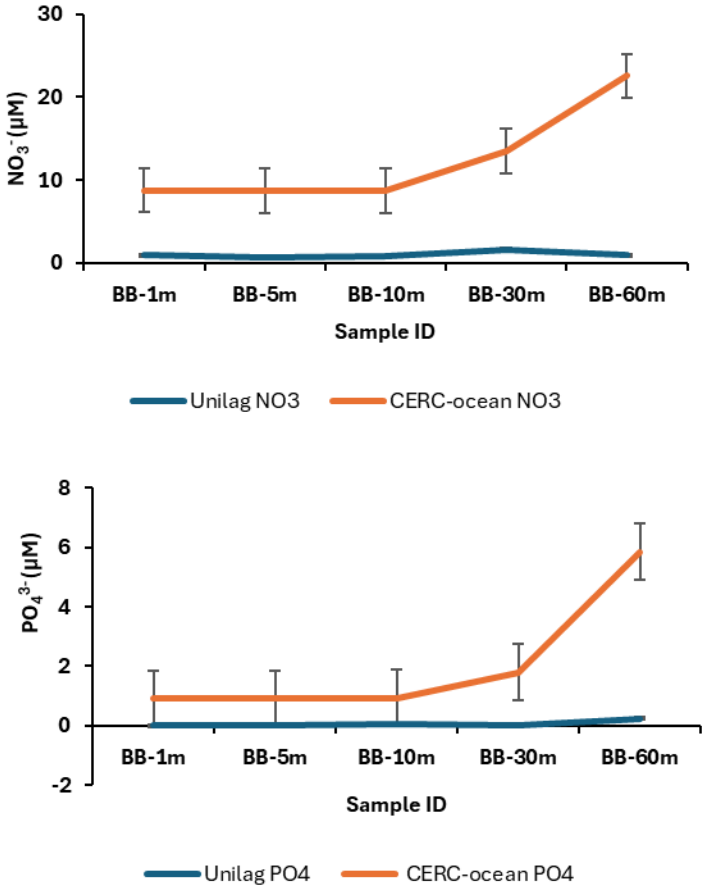


Figure 3.3: *The NO_3^- and PO_4^{3-} concentration reported for water samples from Bedford Basin as analyzed by Unilag and CERC-ocean laboratories.*

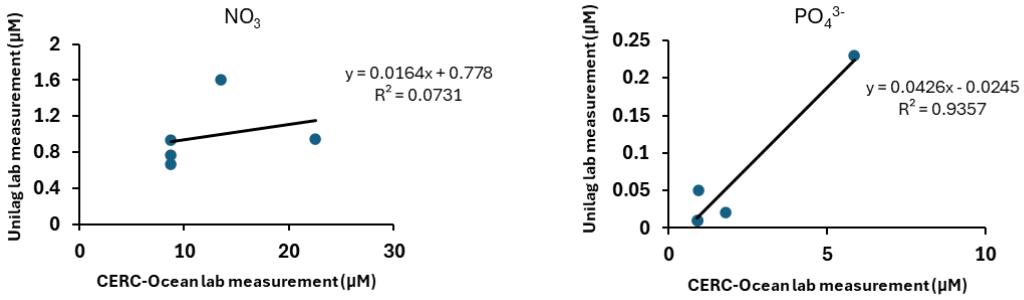


Figure 3.4: *Regression between CERC-Ocean and Unilag lab nutrient measurement for Bedford Basin water samples.*

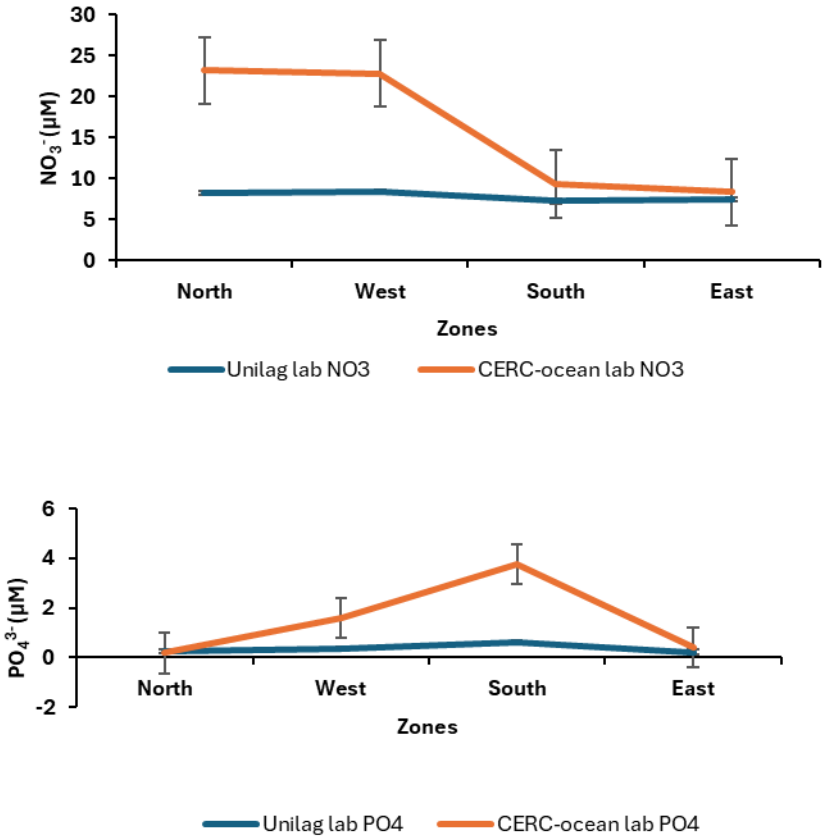


Figure 3.5: *The NO_3^- and PO_4^{3-} concentrations of water samples collected from Lagos lagoon during the wet season as analyzed by Unilag and CERC-ocean laboratories.*

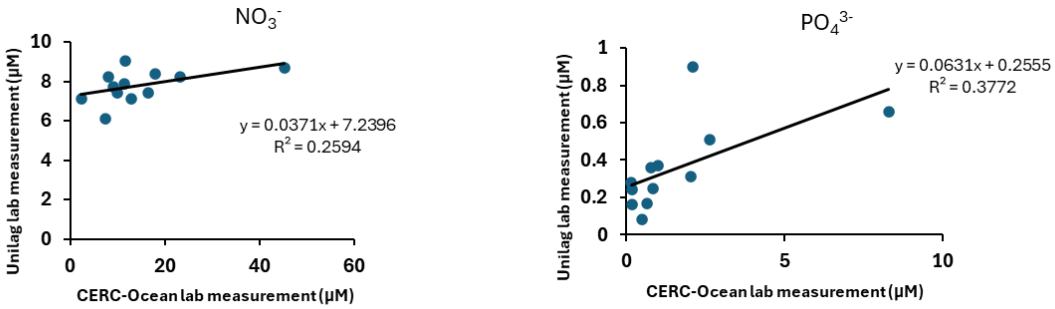


Figure 3.6: *Regression between CERC-Ocean and Unilag lab nutrient measurement for Lagos lagoon wet season water samples.*

3.6.2 Seasonality and spatial distribution of nutrients in Lagos lagoon as analysed by the Unilag laboratory

In the following we will assume that major differences between CERC-Ocean and Unilag nutrient measurements were the result of a systematic error or difference in analysis or workup/reporting so that we can compare, internally, the measurements made locally by Unilag. The Unilag results shows that nitrate (NO_3^-) and phosphate (PO_4^{3-}) concentrations were generally higher during the wet season compared to the dry season. Specifically, NO_3^- concentration ranged from 6.13 ± 0.01 μM to 9.03 ± 0.02 μM with a mean value of 7.78 ± 0.02 μM and 0.52 μM to 1.68 μM a mean value of 0.91 μM during the wet and dry seasons respectively (Fig. 3.7). Spatially, despite the analytical uncertainties, NO_3^- concentration was relatively similar in all the zones. However, the west zone tended toward the highest concentration while the east zone tended toward the lowest values (Fig. 3.7). The PO_4^{3-} concentration ranged from 0.08 ± 0.01 μM to 0.90 ± 0.01 μM with a mean value of 0.36 ± 0.02 μM, and 0.01 μM to 1.17 μM with a mean value of 0.26 μM during the wet and dry seasons respectively (Fig. 3.7). Spatially, the southern zone had the highest concentrations with mean values of 0.60 μM and 0.42 μM in both wet and dry seasons compared to the east zone with the lowest concentration with a mean value of 0.22 μM and 0.07 μM in the wet and dry seasons (Fig. 3.7).

The NO_3^-:PO_4^{3-} ratio for the lagoon was generally higher in the wet season with range 12:1 to 34:1 compared to dry season with range 2:1 to 16:1. Spatially, the north, and east zones had the highest ratios compared to the east and south zones with lower ratios. However, based the on the regression, the actual values could be much higher.

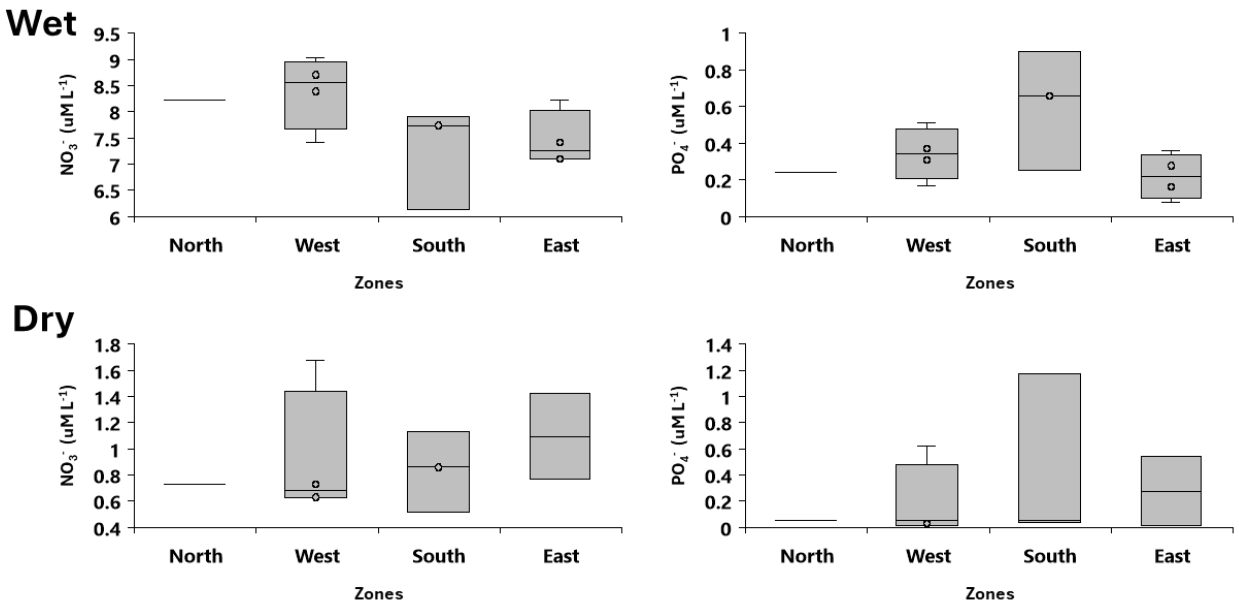


Figure 3.7*: The level of nutrients in Lagos lagoon in both wet and dry season as analysed by Unilag lab.*

3.7 Discussion

3.7.1 Between lab comparison of nutrient analyses

The results of the nutrient analyses for both Lagos lagoon and Bedford Basin samples indicated that the results from the CERC-Ocean and Unilag lab did not agree with each other. The CERC-Ocean laboratory consistently recorded significantly higher nutrient levels for field-collected samples compared to the Unilag laboratory (Figs. 3.3, 3.4, 3.4, and 3.5). It is challenging to pinpoint the causes for this difference; however, we can speculate a few potential sources of error are associated with various steps in sample analyses, including sample collection, analyses, sample transfer and storage as well as data workup and reporting:

1. **Sampling procedure:** The sampling procedure was the same for both laboratories. Therefore, it is unlikely that any differences between labs was associated with this aspect.
2. **Analytical methods and procedures:** The laboratories employed significantly different analytical methods. Unilag utilized manual colorimetric methods, specifically the molybdenum blue method for PO_4^{3-} and the Griess reaction method for NO_3^-. In contrast, CERC-Ocean used the Skalar San++ Continuous Flow Analyzer. Variations in procedure and principles may contribute to some differences in results but this would require further testing and comparison of efficiencies (e.g. of nitrate reduction to nitrite or of colour-forming reactions and/or effects of interferences), standardization, etc.
3. **Data workup and reporting:** After sample analyses, concentrations of nutrients require various calculations including calibration and unit conversions. For example, as noted earlier, reporting concentration in mg L^{-1} could be associated with risk of confusion arising from expressing either in mg L^{-1} of the element ($N\text{-}NO_3^-$) or in mg L^{-1} of the ion (NO_3^-). Such confusion in the conversion processes can lead to variation between lab results. While

specifics of these calculations and data workup were not addressed in our current study, they will be considered in future projects to enhance the accuracy of comparative analyses.

4. **Prolonged storage effects:** Lagos lagoon is likely to have high NH_4^+ and Bedford Basin also has high NH_4^+ (about 50% of DIN) at certain times of the year. Some of this NH_4^+ may be oxidized to $NO_2 + NO_3$ during the prolonged storage. Similarly, prolonged storage time may have resulted to the conversion of other forms of P to PO_4^{3-} during storage. These transformations could lead to elevated PO_4^{3-} levels. However, while the shipping process and longer-term storage of samples at CERC-Ocean compared to Unilag may raise concerns about effects of storage time, the observation of higher nutrient levels in samples from the Bedford Basin, which underwent no shipping and experienced lesser storage time, suggests that variation in storage time is not the primary factor driving the differences in results.

3.7.1.1 Logistical challenges encountered during the project

The execution of the collaborative study to measure and understand nutrient levels in Lagos lagoon relied heavily on efficient sampling and shipping processes and international sharing of resources and samples. However, several logistical challenges emerged throughout these phases, which posed significant hurdles to our research and may have compromised the results. In this section, we delineate these challenges and discuss their implications on the study's progression and outcomes.

1. **Fund transmission and differences in ways of doing business:** As a collaborative study, funding for this project was provided primarily by a grant held by Dalhousie University with significant in-kind support of scientific and technical support from Nigeria partner. Consequently, there was a crucial need to transmit funds from the university to our

Nigerian counterparts. However, this process encountered challenges due to cross-border banking regulations and complications, taking more than three months to complete. The difference in research funding methods between Canada and Nigeria further complicated this process, with Canada using a post-payment, reimbursement method and Nigerian institutions requiring pre-payment. This disparity led to delays in sampling execution, impacting the overall timeline of the study.

2. **Sampling equipment challenges:** The necessary sampling equipment was not readily available locally in Nigeria, necessitating the shipment of some equipment from CERC-Ocean lab. This presented challenges such as equipment loss during transit, duplication of shipping efforts, and incompatibility of gear with local conditions. Equipment designed for specific environmental conditions in Canada sometimes proved unsuitable for the conditions of Lagos lagoon, requiring improvised solutions in the field and modifications that prolonged sampling time and reduced the number of samples obtained.
3. **In-country sample processing challenges:** A significant challenge during the sampling process was the lack of adequate technology and, especially, an irregular power supply within the study area. Basic equipment necessary for sample preparation, analyses, and data interpretation was often unavailable or outdated, prolonging the timeline and necessitating adjustments to the study's objectives.
4. **Customs and import regulation:** Ensuring compliance with diverse regulatory frameworks resulted in delays and bureaucratic procedures at customs checkpoints, leading to prolonged shipping times and added complexities to the logistical workflow. As a result of delays in shipment (including customs clearance), some samples lost integrity or were damaged, reducing sample size and necessitating modifications to the study objective.

5. **Transportation and packaging constraints:** Preserving sample integrity during transit required meticulous packaging protocols. Despite using dry shipper capable of maintaining samples at the required temperature, logistical constraints such as customs delays and inadequate handling during transit led to loss of sample integrity.

3.7.1.2 Recommendations

To address the challenges faced in international collaboration in environmental research, especially with developing countries we recommend the following:

1. **Early budget planning:** Start the budget payment schedule at least six months before the sampling date. This will allow adequate time for funds to clear international banking regulations and for local collaborators to receive funds in a timely manner, enabling better contingency planning.
2. **Pretrial of sampling equipment:** Identify potential compatibility issues beforehand by pretesting the sampling equipment. This will help in selecting equipment that is better suited for local conditions.

By addressing these logistical challenges and making the recommended adjustments, future studies can achieve more reliable and consistent nutrient results in collaborative research settings.

3.7.2 Spatial and temporal variability of nutrients within Lagos lagoon as analysed by the Unilag laboratory

The results from the Unilag laboratory suggests that rainfall or runoff exerts a significant influence on nutrient levels within Lagos lagoon. The elevated concentrations of NO_3^- and PO_4^{3-} during the wet season suggest that a considerable portion of pollutants enters the lagoon during this period. Previous research has consistently shown an increase in nutrient concentrations during the wet season, often attributed to runoff from agricultural fields and untreated sewage (Ladipo et al., 2012;

Nkwoji et al., 2020). Land-based sources, including industrial and domestic waste, contribute to this influx of organic matter into the lagoon through runoff channels (Balogun et al., 2015; Edokpayi & Ayorinde, 2009). Consequently, the influx of organic matter as well as inorganic nutrients from wastewater and sewage can lead to heightened nutrient loading, particularly in the form of nitrogen compounds such as nitrate (El Hamouti et al., 2023).

Spatially, there was less uniformity in NO_3^- distribution across the lagoon compared to PO_4^{3-}, also suggestive of the variations in the influencing factors. In contrast, the south zone, a zone further removed direct river inputs, consistently recording the highest PO_4^{3-} concentration in both seasons, indicating the influence of other localized factors apart from runoff. The observed variability in nutrient distributions indicates the complex interplay of environmental and human-induced factors in shaping nutrient dynamics within the lagoon. Identifying the specific factors driving these variations can be challenging due to the multifaceted nature of coastal ecosystems and the myriads of influences acting on them (Pérez-Ruzafa et al., 2011). This interplay makes it difficult to point out factors particularly influencing the distribution of nutrients. A pre-requisite of course, is high reliability and inter-comparability of the chemical analyses themselves.

Previous studies have highlighted the complexity of nutrient distribution within lagoon environments, emphasizing the role of various factors such as catchment human population, wastewater seepage from septic systems (Costanzo et al., 2001; Schlacher et al., 2005; Fraser et al., 2024; Montes et al., 2013) and atmospheric deposition (Olayinka et al., 2016) in influencing nutrient distribution. Furthermore, the influence of local hydrological processes, sedimentation patterns, and biological interactions within the lagoon can further modulate nutrient distribution, adding to the complexity of the system (Carvalho et al., 2011; Maher et al., 2019; Rahhou et al., 2022).

Generally, the nutrient results from the Unilag laboratory analyses shared some overall agreement with the implication of our stable isotope findings as discussed in Chapter Two of this thesis.

3.8 Conclusions

Water samples from Lagos lagoon and Bedford Basin, including reference material were used for a preliminary intercomparison of nutrient analyses from Unilag and CERC-Ocean laboratory to improve the understanding of nutrient level in Lagos lagoon. Our findings showed good agreement in the measurement of the reference materials however there were major differences in nutrient levels reported by the two laboratories for the field samples, with Unilag laboratory reporting consistently lower values. The logistics of the intercomparison were not optimal and many samples were compromised during transport and storage, complicating the interpretation of the differences. Several factors likely contributed to these variations, including differences in analytical methods and procedures, data workup and reporting, and potential storage effects.

Our findings showed that Unilag laboratory's results with respect to season and spatial variability demonstrated some consistency with the implications of our stable isotope findings, validating the utility of the isotopic measurements in assessing nutrient distribution within Lagos lagoon despite the analytical uncertainties of the nutrient results. Seasonal and spatial variations in nutrient levels were evident, with higher concentrations observed during the wet season, attributable to runoff from agricultural and urban sources.

Logistical challenges encountered during sampling and shipping, such as fund transmission delays, equipment incompatibility, and customs regulations, further complicated our study. These challenges highlight the importance of meticulous planning and coordination in international collaborative research.

To enhance the reliability and consistency of future studies, we recommend early budget planning, pretrial of sampling equipment, and development of contingency plans. Addressing these logistical

challenges will facilitate more accurate and comprehensive nutrient analyses, contributing to better management of coastal ecosystems like Lagos lagoon.

3.9 Future Work

Further work should focus on improving on the interlaboratory nutrient comparison leveraging the challenges and experiences gained from this preliminary study and utilizing only reference materials. The intercomparison should first be conducted between laboratories in Nigeria to identify the possible local challenges. The exercise should include a workshop to be held in West Africa, on sampling techniques, analysis, data workup and reporting procedures. Then, comparison with international laboratories to improve on the local challenges and advance in the establishment of a coordinated pollution monitoring program for the lagoon. Consideration of alternative analytical approaches, such as smartphone-based analytical methods, which are recently gaining attention (Fang et al., 2021; H. Li et al., 2022, 2023; Lin et al., 2024; Zheng et al., 2022), should be considered. These low-cost yet increasingly reliable methods seem to hold promise for studies like this, given limited budgets and access to equipment.

Chapter 4

Conclusions and Future Work

4.1 Conclusions

The studies outlined in this thesis have significantly advanced our understanding of nutrient levels, trophic dynamics, and nutrient measurement practices in Lagos lagoon. Our findings are of potential interest to a wide range of stakeholders, including environmental managers, government officials, policymakers, scientists, health officials, industry representatives, consultants, and the public, who all depend on the lagoon for their livelihoods.

Our data demonstrated that stable isotopes from common biota within the lagoon provide an integrated measurement of nutrient levels. The $\delta^{13}C$ and $\delta^{15}N$ values in both biota and sediments exhibited strong spatial variability with $\delta^{13}C$ strongly reflecting the impact of terrestrial and marine sources of carbon, while $\delta^{15}N$ trophic fractionation. The calculated baseline $\delta^{15}N$ values were generally within the range of natural seawater nitrate and terrestrial soil nitrate, but varied spatially, reflecting terrestrial and marine sources of carbon. Heavier $\delta^{15}N$ values were observed in both sediment and biota from the highly urbanized zones, suggesting sewage inputs. The overall effect of seasonality on $\delta^{13}C$ and $\delta^{15}N$ values was marginal compared to the more pronounced spatial and trophic effects.

The interlaboratory comparative analyses study showed significant differences between labs, the origin of which are not clear but may be illustrative of potential sources of discrepancies in nutrient levels as reported in the literature. It highlighted the analytical capabilities of local laboratories and paved the way for further studies to improve nutrient analyses practices in the lagoon. These efforts will facilitate the establishment of a coordinated monitoring program.

4.2 Future Work

Several promising directions for future research and collaboration emerge from this thesis. First, enhancing the study of stable isotopes in common bioindicators within Lagos lagoon is crucial. This can be achieved by increasing the number of sampling sites within each zone, allowing for a more detailed assessment of local variations and better identification of specific nutrient sources thereby aiding in establishment of standard monitoring locations. Additionally, expanding the scope of biota sampling to include a wider range of trophic levels will provide a more comprehensive understanding of the food web and trophic dynamics within the lagoon.

Secondly, determining the isotopic signatures of different pollution sources, such as river and marine inputs, is essential. This approach will help identify and quantify the respective contributions of these sources to nutrient loading, leading to more targeted and effective management strategies.

Lastly, improving the interlaboratory nutrient comparison is vital. Building on the challenges and experiences from this preliminary study, future comparisons should utilize only reference materials and involve training and intercomparison workshops. Initially, intercomparisons should be conducted between laboratories in Nigeria to identify and address local challenges. Subsequently, comparisons with international laboratories will help improve local practices. The intercomparison and consideration of standard methods; more up-to-date and appropriate methods (including lower-cost methods based on smartphone detection) and distribution and use of reference materials within Nigeria among different groups will advance the establishment of a coordinated pollution monitoring program for the lagoon.

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Appendices

Appendix A: Carbon, nitrogen and bulk isotope data for biota and sediment used for the study

Table A1: Biota carbon, nitrogen and bulk isotope data used for the study.

Station	Season	Type	Species/Genus	Common name	ID	%C of sample	%N of sample	C:N ratio	$\delta^{13}C$ (‰)	$\delta^{13}N$ (‰)
AP (south)	Wet	Fish	*Caranx hippos*	*Jackfish*	E-Jackfish	45.68	14.31	3.19	-17.75	14.23
AP (south)	Wet	Fish	*Chrysichthys nigrodigitatus*	*Catfish*	B-Catfish	45.15	14.13	3.20	-26.60	13.20
AP (south)	Wet	Fish	*Ethmalosa fimbriata*	*Bongafish*	A-Bongafish	44.81	14.35	3.12	-22.76	14.06
AP (south)	Dry	Fish	*Liza grandiquamus*	*Atoko*	Atoko-1	44.51	13.59	3.28	-19.62	10.45
AP (south)	Dry	Fish	*Liza grandiquamus*	*Atoko*	Atoko-1 Dup	44.28	13.74	3.22	-25.46	8.58
AP (south)	Dry	Fish	*Liza grandiquamus*	*Atoko*	Atoko-3	43.97	13.85	3.17	-25.57	8.91
AP (south)	Wet	Fish	*Mugil cephalus*	*Mulletfish*	C-Mugilfish	46.30	14.57	3.18	-17.21	11.99
AP (south)	Wet	Fish	*Pomadasys jubelini*	*Grunterfish*	F-Grunterfish	45.53	14.37	3.17	-20.32	14.14
AP (south)	Wet	Fish	*Pseudotolithus eukogatus*	*Croaker*	G-Craockerfish	45.64	14.28	3.20	-18.37	14.83
AP (south)	Dry	Fish	*Tilapia zillii*	*Tilapia*	Tilapia-1	43.77	13.86	3.16	-22.60	12.69
AP (south)	Dry	Fish	*Tilapia zillii*	*Tilapia*	Tilapia-1 Dup	43.74	13.64	3.21	-23.75	12.84
AP (south)	Dry	Fish	*Tilapia zillii*	*Tilapia*	Tilapia-2	43.90	14.08	3.12	-20.33	11.01
AP (south)	Dry	Fish	*Tilapia zillii*	*Tilapia*	Tilapia-2 Dup	44.53	13.69	3.25	-20.05	12.80
AP (south)	Dry	Fish	*Tilapia zillii*	*Tilapia*	Tilapia-3	44.50	13.51	3.29	-19.77	13.57
EP (east)	Wet	Fish	*Caranx hippos*	*Jackfish*	F-Jackfish	45.96	14.51	3.17	-24.70	14.88
EP (east)	Dry	Fish	*Chrysichthys nigrodigitatus*	*Catfish*	Catfish-1	46.64	14.77	3.16	-33.42	10.84
EP (east)	Dry	Fish	*Chrysichthys nigrodigitatus*	*Catfish*	Catfish-2	46.19	13.83	3.34	-30.15	8.27
EP (east)	Wet	Fish	*Ethmalosa fimbriata*	*Bongafish*	D-Bongafish	43.88	14.10	3.11	-25.17	13.44
EP (east)	Wet	Fish	*Ethmalosa fimbriata*	*Bongafish*	F1-Bongafish	45.14	14.45	3.12	-25.95	14.25
EP (east)	Dry	Fish	*Gymnarchus niloticus*	*Snakefish*	Snakefish-1	46.17	14.32	3.22	-31.86	8.71
EP (east)	Wet	Fish	*Monodactylus sebae*	*Moonyfish*	A-Moonyfish	45.79	14.52	3.15	-24.00	16.14
EP (east)	Wet	Fish	*Mugil cephalus*	*Mulletfish*	G-Mugilfish	45.59	14.16	3.22	-21.63	12.04
EP (east)	Wet	Fish	*Pomadasys jubelini*	*Grunterfish*	C-Grunterfish	46.46	14.25	3.26	-25.72	12.93
EP (east)	Dry	Fish	*Sarotherodon melanotheron*	*Tilapia*	Tilapia-1	43.44	13.91	3.12	-33.85	7.41
EP (east)	Dry	Fish	*Sarotherodon melanotheron*	*Tilapia*	Tilapia-3	45.20	14.47	3.12	-34.34	6.52
IK (north)	Wet	Fish	Chrysichthys nigrodigitatus	Catfish	F-Chrysifish	46.02	14.45	3.19	-25.70	15.69
IK (north)	Wet	Fish	Monodactylus sebae	Moonyfish	A-Moomyfish	48.00	13.02	3.69	-26.41	17.23
IK (north)	Wet	Fish	Mugil cephalus	Mulletfish	E-Mulletfish	47.94	13.99	3.43	-22.90	15.15

Table A1: Biota carbon, nitrogen and bulk isotope data used for the study continues.

Station	Season	Type	Species/Genus	Common name	ID	%C of sample	%N of sample	C:N ratio	$\delta^{13}C$ (‰)	$\delta^{13}N$ (‰)
IK (north)	Wet	Fish	Not identified	Fish (unknown)	Specie-2	43.97	13.94	3.15	-31.26	11.17
IK (north)	Wet	Fish	Not identified	Fish (unknown)	Specie-3	46.15	14.64	3.15	-33.37	11.04
IK (north)	Wet	Fish	Not identified	Fish (unknown)	Specie-3 Dup	45.16	14.35	3.15	-29.55	10.99
IK (north)	Wet	Fish	Not identified	Fish (unknown)	Specie-3 Trip	45.12	14.44	3.12	-31.93	7.58
IK (north)	Dry	Fish	Polydractylus quadrifilis	Threadfish	G-Threadfish	45.71	14.45	3.16	-23.78	11.22
IK (north)	Dry	Fish	Pomadasys jubelini	Grunterfish	B2-Gruntarfish	73.01	22.52	3.24	-19.71	15.42
IK (north)	Dry	Fish	Pseudotolithus eukogatus	Croaker	B1-Craoker	48.10	13.82	3.48	-24.23	15.34
IK (north)	Dry	Fish	Sarotherodon melanotheron	Tilapia	Tilapia-1	44.08	13.93	3.16	-31.26	12.79
IK (north)	Dry	Fish	Sarotherodon melanotheron	Tilapia	Tilapia-2	45.27	13.38	3.38	-29.13	14.54
IK (north)	Dry	Fish	Sphyraena barracuda	Baracuda	C-Barracudafish	45.10	14.27	3.16	-25.35	15.95
MA (west)	Wet	Fish	Elops lacerta	Ladyfish	D-Ladyfish	46.34	14.27	3.25	-20.94	9.63
MA (west)	Dry	Fish	Lutjanus agennes	Redsniper	Redsniper-1	91.32	27.94	3.27	-27.32	14.68
MA (west)	Dry	Fish	Lutjanus agennes	Redsniper	Redsniper-2	46.50	14.22	3.27	-22.57	14.44
MA (west)	Dry	Fish	Lutjanus agennes	Redsniper	Redsniper-3	30.85	9.63	3.20	-17.53	11.61
MA (west)	Wet	Fish	Malapterurus electicus	Catfish	C-catfish	67.14	20.59	3.26	-21.61	12.35
MA (west)	Dry	Fish	Notopterus notopterus	Folo	Folo-1	50.33	11.07	4.55	-28.95	13.02
MA (west)	Dry	Fish	Notopterus notopterus	Folo	Folo-2	47.06	12.46	3.78	-28.15	13.08
MA (west)	Dry	Fish	Notopterus notopterus	Folo	Folo-3	46.70	12.62	3.70	-27.94	12.34
MA (west)	Dry	Fish	Sphyraena barracuda	Baracuda	Baracuda-1	46.40	14.08	3.29	-17.53	13.57
MA (west)	Dry	Fish	Sphyraena barracuda	Baracuda	Baracuda-2	44.27	13.74	3.22	-17.52	11.69
MA (west)	Dry	Fish	Sphyraena barracuda	Baracuda	Baracuda-2 Dup	44.27	13.87	3.19	-17.46	11.71
MA (west)	Dry	Fish	Sphyraena barracuda	Baracuda	Baracuda-3	43.77	13.86	3.16	-17.43	12.10
MA (west)	Dry	Fish	Tilapia zillii	Tilapia	Tilapia-1	43.68	13.84	3.16	-25.11	14.17
MA (west)	Dry	Fish	Tilapia zillii	Tilapia	Tilapia-2	42.59	13.66	3.12	-23.47	14.71
MA (west)	Dry	Fish	Tilapia zillii	Tilapia	Tilapia-3	43.46	14.03	3.10	-25.06	15.02
AP (south)	Dry	Invertebrate	Callinectes amnicola	Crab	Crab-1	40.78	12.96	3.15	-28.30	8.02
AP (south)	Wet	Invertebrate	Callinectes sapidus	Crab	D-BlueCrab	42.45	12.97	3.27	-26.47	10.78

Table A1: Biota carbon, nitrogen and bulk isotope data used for the study continues.

Station	Season	Type	Species/Genus	Common name	ID	%C of sample	%N of sample	C:N ratio	$\delta^{13}C$ (‰)	$\delta^{13}N$ (‰)
EP (east)	Wet	Invertebrate	Machrobrachium specie	Shrimp	B-Shrimp	45.14	13.94	3.24	-25.75	10.77
EP (east)	Wet	Invertebrate	Machrobrachium specie	Shrimp	H-Shrimp	45.38	14.37	3.16	-27.61	11.36
EP (east)	Dry	Invertebrate	Penaeus monodon	Shrimp	Shrimp-1	43.80	13.89	3.15	-29.17	7.31
EP (east)	Dry	Invertebrate	Penaeus monodon	Shrimp	Shrimp-2	45.98	13.51	3.40	-33.26	7.17
EP (east)	Dry	Invertebrate	Penaeus monodon	Shrimp	Shrimp-3	45.61	14.04	3.25	-32.37	7.33
IK (north)	Dry	Invertebrate	NA		NA	NA	NA	NA	NA	NA
MA (west)	Dry	Invertebrate	Callinectes amnicola	Crab	Crab-1	42.91	13.88	3.09	-23.55	13.74
MA (west)	Dry	Invertebrate	Callinectes amnicola	Crab	Crab-2	45.31	14.44	3.14	-17.51	11.99
MA (west)	Dry	Invertebrate	Callinectes amnicola	Crab	Crab-2 Dup	40.97	13.27	3.09	-23.82	13.58
MA (west)	Dry	Invertebrate	Callinectes amnicola	Crab	Crab-3	40.94	13.09	3.13	-22.28	13.08
MA (west)	Wet	Invertebrate	Machrobrachium specie	Shrimp	A-Shrimp	45.15	13.64	3.31	-25.72	11.54
MA (west)	Wet	Invertebrate	Penaeus monodon	Shrimp	B-Shrimp	44.65	14.10	3.17	-22.78	10.72
MA (west)	Dry	Invertebrate	Penaeus notialis	Shrimp	Shrimp-1	42.68	13.53	3.15	-23.13	8.49
MA (west)	Dry	Invertebrate	Penaeus notialis	Shrimp	Shrimp-2	44.60	14.21	3.14	-20.24	9.34
MA (west)	Dry	Invertebrate	Penaeus notialis	Shrimp	Shrimp-3	45.35	14.41	3.15	-21.58	8.75
MA (west)	Dry	Invertebrate	Penaeus notialis	Shrimp	Shrimp-4	43.15	13.76	3.14	-20.01	9.37
AP (south)	Wet	Mangrove	Eichhornia grassipis	Mangrove	Mcrophyte	36.57	5.01	7.31	-31.43	-0.59
EP (east)	Dry	Mangrove	Eichhornia grassipis	Mangrove	Mcrophyte	38.54	3.64	10.60	-30.25	7.53
IK (north)	Dry	Mangrove	Eichhornia grassipis	Mangrove	Mcrophyte	36.51	3.85	9.49	-30.52	16.64
MA (west)	Dry	Mangrove	Eichhornia grassipis	Mangrove	Mcrophyte	36.37	4.03	9.03	-29.05	7.43
IK (north)	Dry	Fish	Not identified	Fish (unknown)	Specie-1	60.97	8.12	7.51	-28.29	6.12
IK (north)	Dry	Fish	Not identified	Fish (unknown)	Specie-1 Dup	56.01	10.41	5.38	-27.33	5.70
IK (north)	Dry	Fish	Not identified	Fish (unknown)	Specie-1 Trip	61.30	8.69	7.06	-28.18	5.77

Appendix B: Table of mean values of stable isotope results

Table B1: The mean values of $\delta^{13}C$ and $\delta^{15}N$ values of different biota for different seasons and locations. "n" represents the number of the samples fro m which the mean value was obtained.

Mean values	Season		Zone				Type		
	Dry (n = 50)	Wet (n= 29)	Apapa (South) (n = 16)	Epe (East) (n = 18)	Ikorodu (North) (n = 17)	Makoko (West) (n = 29)	Fish (n =57)	Invertebrates (n = 19)	Mangrove leaves (n = 4)
$\delta^{13}C$	-25.80	-23.61	-22.18	-28.14	-27.54	-23.41	-24.81	-24.51	-30.31
(‰)	±5.20	±3.18	±3.50	±3.87	±3.78	±3.49	±4.77	±4.27	±0.98
$\delta^{15}N$	10.90	12.99	12.01	10.73	12.64	10.13	12.26	10.36	7.75
(‰)	±2.86	±3.38	±2.15	±3.33	±3.77	±3.45	±2.81	±2.25	±7.04

Table B2: Summary of season-zone interaction of biota.

Zone	Season			
	Wet		Dry	
	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)
Apapa	-22.15±4.79	13.32±1.45	-22.21±2.39	10.99±2.11
Epe	-25.21±1.69	13.34±1.74	-32.30±1.90	7.95±1.27
Ikorodu	-23.96±2.19	15.14±1.86	-29.28±3.08	10.23±3.84
Makoko	-24.51±3.83	8.93±4.77	-22.56±4.06	12.09±2.17

Table B3: Summary means of zone-type interaction of biota.

Zone	Type					
	Fish		Invertebrates		Mangrove leaves	
	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)
Apapa	-21.44±3.42	12.38±1.96	-27.39±1.29	9.40±1.95	-	-
Epe	-28.10±4.38	11.64±3.22	-27.39±1.29	8.79±2.09	-30.25	7.53
Ikorodu	-27.40±3.70	11.98±3.94	-29.63±3.16	-	-30.52	16.64
Makoko	-22.57±4.38	12.94±1.51	-22.63±2.52	11.20±1.91	-30.24±1.68	3.42±5.67

Appendix C: Table of nutrient results from Unilag and CERC-Ocean laboratories

Table C1: Concentration of nutrients in Bedford Basin water samples as measured in University of Lagos and Dalhousie University CERC-ocean laboratory.

Sample ID	Unilag lab	CERC-ocean lab	Unilag lab	CERC-ocean lab	Unilag lab	CERC-ocean lab
	PO_4^{3-}		NO_3^-		NO_3^- / PO_4^{3-}	
	(µM)					
BB-1m	0.01±0.00	0.91±0.00	0.93±0.06	8.77±0.04	84:1	10:1
BB-5m	0.01±0.00	0.90±0.03	0.67±0.13	8.74±0.01	61:1	10:1
BB-10m	0.05±0.04	0.94±0.00	0.77±0.14	8.74±0.16	17:1	9:1
BB-30m	0.02±0.02	1.80±0.00	1.60±0.53	13.50±0.05	76:1	8:1
BB-60m	0.23±0.04	5.85±0.14	0.94±0.48	22.55±0.18	4:1	4:1

Table C2: Concentration of nutrients in Lagos lagoon water samples during the dry season as measured in the University of Lagos laboratory.

Zones	Stations	PO_4^{3-}	NO_3^-	NO_3^- / PO_4^{3-}
		(µM)		
North	Ikorodu	0.05	0.73	14:1
West	Oworo	0.62	0.63	
	Unilag	0.07	0.63	
	Makoko	0.03	0.73	
	Iddo	0.01	1.68	
Mean		**0.19**	**0.92**	5:1
South	Apapa	0.05	1.13	
	Coconut	1.17	0.52	
	Atlascove	0.04	0.86	
Mean		**0.42**	**0.83**	2:1
East	Epe	0.54	1.42	
	Ajah	0.01	0.77	
Mean		**0.07**	**1.10**	16:1
Grand mean			**0.90**	

Appendix D: Lagos lagoon water and sediment chemistry

Table D1: Dry and wet season water chemistry of Lagos lagoon

Station	Temp (°C)	pH	ORP (mV)	Conductivity (uS/cm)	Turbidity (NTU)	DO (mg/L)	% DO	TDS (mg/L)	Salinity (ppt)	Acidity (mg/L)	Alkalinity (mg/L)	Chloride (mg/L)	Hardness (mg/L)	TS (mg/L)	TSS (mg/L)	BOD (mg/L)	COD (mg/L)	PO_4^{3-} (P) (mg/L)	Total Phosphorus (mg/L)	NO_3^- (N) (mg/L)	SiO_2 (mg/L)
Dry season																					
Ikorodu	30.2	8.06	80	8.49	20.7	6.81	92.8	5350	4.71	3.42	48	2808	836	6061	711	54.48	80.64	0.005	0.014	0.045	13.18
Iyanaoworo	30.8	7.69	172	15.3	18	7.85	110.5	9470	8.87	9.12	60	5054	1734	21932	12462	94.61	263.42	0.059	0.642	0.039	10.97
Unilag	30.05	7.79	185	18.7	16.6	8.11	114.1	11600	11.05	6.84	60	6279	1958	19284	7684	63.08	319.87	0.007	0.703	0.039	8.71
Makoko	29.93	7.91	170	21	12.3	7.94	112.4	13000	12.53	3.42	48	6994	2040	27096	14096	71.68	411.26	0.003	0.006	0.045	8.71
Iddo	29.16	7.77	175	29.4	13.5	6.76	97.4	18200	18.18	3.42	60	10669	2244	19320	1120	74.55	435.46	0.001	0.706	0.104	5.37
Apapa	29.62	7.58	184	33.5	7.5	5.73	84.5	20400	20.95	7.98	72	11613	3060	25054	4654	60.21	438.14	0.005	0.119	0.07	5.44
Coconut	30.78	6.87	214	31.2	51.3	2.03	30.3	19100	19.38	14.82	36	10848	2224	20338	1238	143.36	438.14	0.111	0.272	0.032	7.58
Atlascove	29.64	7.48	120	33.4	5.8	5.73	84.5	20400	20.98	5.7	60	11869	2632	22525	2125	91.75	440.83	0.004	0.01	0.053	4.72
Epe/Leki	30.26	7.93	108	23.3	16.1	8.13	116.7	14500	14.07	4.56	48	8040	1918	154512	14012	97.48	435.46	0.014	0.239	0.088	7.21
Ajah	29.78	8.13	123	9.02	19.1	9.15	124	5680	5.03	1.14	36	2935	898	6353	673	48.74	96.77	0.001	0.03	0.048	7.21
VGC	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ikate	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Wet season																					
Ikorodu	27.4	7.77	189	0.26	182	6.95	-	170	0.12	21.6	248.6	67.6	728	184	14	60.1	178.4	0.023	-	0.51	-
Iyanaoworo	27.7	7.58	133	0.45	157	5.17	-	290	0.21	38.4	113	118.5	170.6	480	190	68.3	198.8	0.029	-	0.52	-
Unilag	27.9	7.21	150	0.46	109	3.88	-	300	0.22	67.2	158.2	124.2	212.2	410	110	101.7	222.3	0.035	-	0.56	-
Makoko	28.2	7.39	115	0.55	116	5.18	-	310	0.26	84	158.2	142.8	187.2	442	132	69.4	180.1	0.048	-	0.54	-
Iddo	27.7	7.64	113	9.68	5.43	5.35	-	6400	5.43	57.6	135.6	3010.5	2132	6640	240	75.6	307	0.016	-	0.46	-
Apapa	28.5	7.25	150	9.01	43.7	2.7	-	5680	5.02	93.6	135.6	2781.6	532.5	5972	292	135.4	317.3	0.063	-	0.48	-
Coconut	28.1	7.33	77	9.33	36.2	4.16	-	5880	5.22	199.2	90.4	2898.3	445.1	6270	390	94.4	331.5	0.085	-	0.49	-
Atlascove	28.5	7.28	157	9.17	29.7	7.12	-	5780	5.12	52.8	203.4	2864.8	1716	6050	270	72.8	318.8	0.024	-	0.38	-
Epe/Leki	28.3	7.16	176	2.87	58.89	8.25	-	1880	1.47	52.8	158.2	810.5	307.8	2132	252	77.9	207.9	0.027	-	0.44	-
Ajah	28.1	6.66	213	0.6	95.9	7.07	-	380	0.29	103.2	135.6	161.3	133.1	564	184	70.7	239.1	0.034	-	0.44	-
VGC	28.0	6.75	211	0.7	127	6.81	-	450	0.58	105.6	180.8	325.2	199.7	552	102	69.9	234	0.008	-	0.51	-
Ikate	28.3	7	192	1.17	84.8	7.07	-	1050	0.39	57.6	248.6	236.5	416	1236	186	76.8	237.9	0.015	-	0.46	-

Table D2: Dry and wet season sediments chemistry of Lagos lagoon

Station	pH	Conductivity (mS/cm)	Depth (m)	Bioavailable PO43- (P) (mg/kg)	Total Phosphorus (mg/kg)	Bioavailable NO3- (N) (mg/kg)	Total Nitrogen (mg/kg)
			Dry season				
Ikorodu	4.3	0.32	2.5	1.12	1.4	3.65	5.39
Iyanaoworo	4.13	0.68	2	5.48	5.89	5.66	9.4
Unilag	3.55	1.83	3	1.81	3.21	5.85	9.52
Makoko	6.1	0.68	2	2.39	2.72	2.24	5.09
Iddo	5.48	0.29	4	6.24	7.07	1.53	2.15
Apapa	6.45	0.74	3	2.57	3.03	1.99	3.44
Coconut	5.02	0.77	1.5	14.06	17.59	2.08	12.23
Atlascove	4.7	0.59	3	0.05	0.13	2.15	2.98
Epe/Lekki	4.63	0.4	3	1.55	2.08	2.14	6.13
Ajah	4.52	0.46	2.5	0.61	1.18	2.29	4.39
VGC	-	-	-	-	-	-	-
Ikate	-	-	-	-	-	-	-
			Wet season				
Ikorodu	6.02	1.22	2.5	4.83	-	2.46	-
Iyanaoworo	6.15	2.22	2	3.22	-	2.79	-
Unilag	6.59	2.1	3	2.08	-	2.54	-
Makoko	6.8	2.43	2	0.16	-	2.45	-
Iddo	6.15	3.4	4	2.57	-	3.04	-
Apapa	6.56	2.83	3	2.11	-	2.67	-
Coconut	6.83	5.42	1.5	19.83	-	2.18	-
Atlascove	6.94	3.92	3	10.21	-	2.83	-
Epe/Lekki	6.27	2.26	3	2.08	-	2.66	-
Ajah	6.87	2.67	2.5	3.91	-	2.75	-
VGC	6.55	4.98	-	13.18	-	2.98	-
Ikate	6.25	4.42	-	9.89	-	2.3	-