Advancing Blue Economy In The Indian Ocean:

A Case Of The Fisheries Sector.

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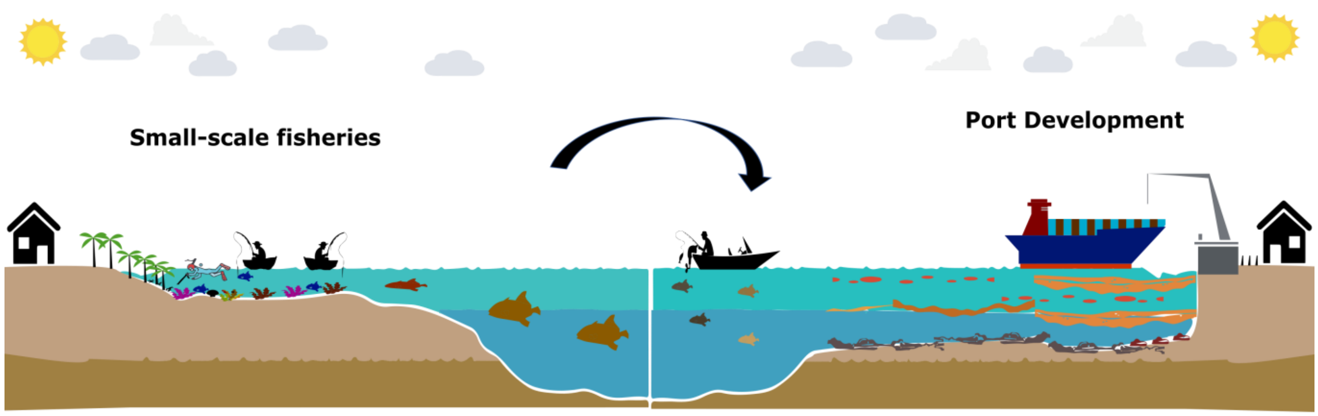

Impact of port development
On small-scale fisheries

Preface

This cumulative thesis focused on the assessment of blue economy sustainability in the Indian Ocean, where there is significant interest in expanding ocean-based activities to increase the region's economic prospects. The PhD work was conducted at the Leibnitz Institute of Baltic Sea Research (IOW) and Macquarie University from October 2018 to March 2022. Four case studies in the fisheries sector are used examples. The Canadian Fisheries Research Network's proposed fisheries sustainability framework (CFRN) is usedas a lens to bring out challenges and opportunities in the different elements of fisheries suitability in the region. The case studies form different independent publications and are described below. Two of the case studies are published in a refereed journal. One manuscript is under review, and one manuscript is under preparation.

Publication 1.

Environmental controls of billfish species in the Indian Ocean and implications for their management and conservation.

Pascal Thoya, Nelly Kadagi, Nina Wambiji, Samuel Mackey Williams, Julian Pepperell, Christian Möllmann, Kerstin Schiele, Joseph Maina

The study was designed in collaboration with Dr Nelly Kadagi and Dr Nina Wambiji, with participation from the other authors, and is part of the WIOMSA billfishWIO research project's output. I did the formal analysis and examination of the results and wrote the first draft of the manuscript. All authors contributed to inspecting preliminary results and writing the subsequent drafts. This paper was published in Wiley, Diversity and Distribution.

Publication 2.

Policy gaps in the East African Blue economy: Perspectives of small-scale fishers on port development in Kenya and Tanzania.

Pascal Thoya, Vera Horigue, Christian Möllmann, Joseph Maina, Kerstin Silke Schiele

The study is the product of a research grant given to me by WIOMSA to investigate the effects of port development on small-scale fishers in East Africa. I designed the study, conducted the analysis, and wrote the first draft of the paper. The co-authors collaborated on the results interpretation, review, and subsequent drafts writing. This case study has been acepted for publication in the Frontier in Marine Science, In a special Research Topic, African Ocean Stewardship: Navigating Ocean Conservation and Sustainable Marine and Coastal Resource Management in Africa.

Publication 3.

The extent of IUU fishing and the role of governance in the Indian Ocean

Pascal Thoya, Sarah Glaser, Vera Horigue, Christian Möllmann, Joseph Maina, Kerstin Schiele

The study was designed in collaboration with Dr Sarah Glaser, with inputs from the other authors. All authors contributed to the inspection of preliminary results and the evaluation of the work. I did the formal analysis and examination of the results and wrote the first draft of the manuscript. By the time of thesis submission, the manuscript was still under preparation for publication.

Publication 4.

AIS and VMS Ensemble Can Address Data Gaps on Fisheries for Marine Spatial Planning

Pascal Thoya, Joseph Maina , Christian Möllmann , and Kerstin Schiele

I developed the study idea with Dr Kerstin Schiele and Dr Joseph Maina, I did all the study's analyses, and I evaluated the results with the help of all the co-authors. I wrote the original draft of the text. The subsequent drafts and review were completed with the participation of all co-authors. This study was published in MDPI, Sustainability 2021, 13 (7), 3769; in the Special Issue, Maritime Spatial Planning for Sustainable Fisheries, https://doi.org/10.3390/su13073769

Other scientific contributions achieved during the study period but not included in the thesis:

There are three main contributions that are not part of this thesis; however, my contribution to these publications benefits from the experiences of these thesis work.

1. ***Pascal, Thoya**, and Tim M. Daw. "Effects of assets and weather on small-scale coastal fishers access to space, catches and profits." Fisheries Research 212 (2019): 146-153.*

This work is related to case study 2 was designed by Dr Tim Daw. I helped with data analysis and the writing of the manuscript.

2. ***Pascal, Thoya.,** Kaunda-Arara, B., Omukoto, J., Munga, C., Kimani, E. and Tuda, A.O., 2019. Trawling effort distribution and influence of vessel monitoring system (VMS) in Malindi-Ungwana Bay: Implications for resource management and marine spatial planning in Kenya. Marine Policy, 109, p.103677.*

This work is related to case studies 3 and 4 in this thesis work. I designed the study with the help of my co-authors. I also participated in data analysis and manuscript writing.

3. *von Thenen, Miriam, Aurelija Armoškaitė, Víctor Cordero-Penín, Sara García-Morales, Josefine B. Gottschalk, Débora Gutierrez, Malena Ripken,* ***Pascal Thoya****, and Kerstin S. Schiele. "The Future of Marine Spatial Planning—Perspectives from Early Career Researchers." Sustainability 13, no. 24 (2021): 13879*

In this publication, I led in the writing of the section on "Blue Governance: Towards Social-Ecological Well-Being", which reflects some of the conclusions made in this thesis work.

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Abbreviations

Abbreviation	*Definition*
ABNJ	Areas Beyond National Jurisdiction
AIS	Automatic Identification System
BE	Blue economy
BMU	Beach Management Unit
CFRN	Canadian Fisheries Research Network
CV	coefficients of variation
EA	East Africa
EAFM	Ecosystem Approach to Fisheries Management
EBFM	Ecosystem-based fisheries management
EBM	Ecosystem-based management
EEZ	Exclusive Economic Zone
EEZ	Exclusive Economic Zone
EIA	Environmental Impacts Assessment
EMA	Environmental Management Act
EMCA	Environmental Management and Cooperation Act
GAM	Generalized additive model
GBM	Gradient Boosting Machine
GFW	Global Fishing Watch data
GoK	Government of Kenya
ICES	International Council for the Exploration of the Seas
IMO	International Maritime Organization
IO	Indian Ocean
IOTC	Indian Ocean Tuna Commission
IUU	Illegal, unreported, and unregulated
MLD	Mixed layer depth
MCS	Monitoring, control, and surveillance
MPA	Marine Protected Areas
OBIS	Ocean Biodiversity Information System
RF	Random Forests
RFMO	Regional Fisheries Management Bodies
SDG	Sustainable Development Goals
SDM	Species distribution model
SEA	strategic environmental assessment
SPAEF	SPAtial EFficiency metric
SSF	Small-scale fisheries
TAC	Total allowable catch
TSS	True skill statistic
VIF	Variance inflation factor
VMS	Vessel Monitoring Systems
WIO	Western Indian Ocean

Summary

The Indian Ocean is a significant ocean basin with diverse biodiversity. The basin substantially contributes to food security, accounting for around 15% of the world's wild-caught marine fish. Artisanal fisheries are prevalent in coastal regions and provide food and livelihood to the coastal population, accounting for most of this fishery's production. In addition, the region is home to a population with significant economic and sociocultural differences. Many nations in the region are classified as low-income countries with significant structural barriers to long-term growth. The region is garnering significance as a frontier to economic development because of governments' recent interest in growing the ocean sectors, often known as blue economy development. With economic development as the driving force behind the blue economy, the question of the drive's potential influence on other areas of development, such as ecological and socio-economic sustainability, arises. The blue economy is increasingly being recognized as requiring consideration of four pillars of sustainability: economic, social, environmental, and institutional.

In this thesis the four pillars of sustainability, are interrogated in the indian ocean to highlight the present issues and opportunities that come with the region's blue economy growth. The thesis focuses on the challenges and opportunities for a sustainable fisheries sector, with the results being projected for the larger blue economy sustainability. The thesis takes a three-pronged approach: first, four case studies of fisheries are given: Three case studies highlight the issues that the region's four pillars of sustainability confront in the fisheries sector, while one case study highlights some potential prospects for achieving a sustainable fisheries sector. The second section incorporates the difficulties and challenges within the fisheries sustainability framework proposed by the Canadian Fisheries Research Network (CFRN). The last section incorporates the findings of the mapping of fisheries sustainability challenges into the larger blue economy.

My findings reveal that the fisheries sector has several challenges that cut across the four pillars of sustainability, including overfishing, pollution, and the marginalization of indigenous groups. These issues, particularly those affecting the ecological aspects of sustainability, pose a significant barrier to the sector's expansion. Additional institutional constraints, such as a lack of administrative competence and coordination between national and regional organizations, exacerbate the problems. An all-inclusive and collaborative governance at the national and regional levels is just as essential as other fisheries management techniques, which leads me to recommend marine spatial planning (MSP) as a key instrument for resolving these issues in the region.

Looking at the potential for marine sector growth in the IO, the findings of this thesis show that institutional and governance factors need to be enhanced to build a sustainable blue economy in the region, and we suggest MSP as one way to do so.

Zusammenfassung

Der Indische Ozean ist ein bedeutendes Meeresbecken mit einer großen biologischen Vielfalt. Das Becken trägt wesentlich zur Ernährungssicherheit bei und liefert etwa 15 % des weltweit wild gefangenen Meeresfisches. Die handwerkliche Fischerei ist in den Küstenregionen weit verbreitet und bietet der Küstenbevölkerung Nahrung und Lebensunterhalt, womit sie den größten Teil der Fischereiproduktion ausmacht. Außerdem lebt in der Region eine Bevölkerung mit erheblichen wirtschaftlichen und soziokulturellen Unterschieden. Viele Länder in der Region werden als einkommensschwache Länder mit erheblichen strukturellen Hindernissen für langfristiges Wachstum eingestuft. Die Region gewinnt an Bedeutung als Schwellengebiet für die wirtschaftliche Entwicklung, da die Regierungen in jüngster Zeit ein großes Interesse an der Entwicklung des Meeressektors haben, was oft als *Blue Economy* bezeichnet wird. Da die wirtschaftliche Entwicklung die treibende Kraft hinter *Blue Economy* ist, stellt sich die Frage nach ihrem potenziellen Einfluss auf andere Entwicklungsbereiche, wie etwa ökologische und

sozioökonomische Nachhaltigkeit. Es wird zunehmend anerkannt, dass *Blue Economy* die Berücksichtigung von vier Säulen der Nachhaltigkeit erfordert: wirtschaftliche, soziale, ökologische und institutionelle.

In dieser Arbeit untersuche ich die Säulen der Nachhaltigkeit in der Region, um die aktuellen Probleme und Chancen aufzuzeigen, die mit dem Wachstum von *Blue Economy* in der Region einhergehen. Der Schwerpunkt der Arbeit liegt auf den Herausforderungen und Chancen für einen nachhaltigen Fischereisektor, wobei die Ergebnisse auf die Nachhaltigkeit der *Blue Economy* im Allgemeinen projiziert werden. Die Arbeit verfolgt einen dreigleisigen Ansatz: Zunächst werden vier Fallstudien zur Fischerei vorgestellt: Drei Fallstudien beleuchten die Probleme, mit denen die vier Säulen der Nachhaltigkeit in der Region im Fischereisektor konfrontiert sind, während eine Fallstudie einige potenzielle Perspektiven für die Verwirklichung eines nachhaltigen Fischereisektors aufzeigt. Der zweite Abschnitt befasst sich mit den Schwierigkeiten und Herausforderungen innerhalb des vom Canadian Fisheries Research Network (CFRN) vorgeschlagenen Nachhaltigkeitsrahmens für die Fischerei. Im letzten Abschnitt werden die Ergebnisse der Einordnung der Nachhaltigkeitsherausforderungen der Fischerei in einem größeren Rahmen der *Blue Economy* dargestellt.

Meine Ergebnisse zeigen, dass der Fischereisektor mit mehreren Herausforderungen konfrontiert ist, die die vier Säulen der Nachhaltigkeit betreffen, darunter Überfischung, Verschmutzung und die Marginalisierung indigener Gruppen. Diese Probleme, insbesondere diejenigen, die die ökologischen Aspekte der Nachhaltigkeit betreffen, stellen ein erhebliches Hindernis für die Expansion des Sektors dar. Zusätzliche institutionelle Zwänge wie mangelnde Verwaltungskompetenz und Koordination zwischen nationalen und regionalen Organisationen verschärfen die Probleme. Ich bin der Meinung, dass eine allumfassende und kooperative Verwaltung auf nationaler und regionaler Ebene ebenso wichtig ist wie andere Fischereimanagementtechniken, was mich dazu veranlasst, die marine Raumplanung (MSP) als Schlüsselinstrument zur Lösung dieser Probleme in der Region zu empfehlen.

Mit Blick auf das Wachstumspotenzial des Meeressektors im Indischen Ozean zeigen die Ergebnisse dieser Arbeit, dass die institutionellen sowie Verwaltungsfaktoren verbessert werden müssen, um eine nachhaltige *Blue Economy* in der Region aufzubauen. Die marine Raumplanung bietet diese Möglichkeit.

Chapter1. General Introduction.

In November 2018, the global community met for the first time in Nairobi, Kenya, to deliberate on pathways towards achieving a sustainable blue economy. From the deliberation of the first sustainable blue economy conference, it was clear that governments, international and regional agencies are strengthening their commitment to sustainable management of ocean spaces by seeking solutions to achieve a sustainable blue economy (Outa et al., 2021). The discourse that inspired this conference is the current shift and upsurge in ocean-based developments that are threatening the sustainability of marine resources. The use of the ocean has shifted during the previous few decades from purely fisheries-dominated sectors to the expansion of other sectors such as oil and gas, shipping, aquaculture, port infrastructure, tourism, and mining (Hampton and Jeyacheya, 2020; Pauly, 2018; Smith-Godfrey, 2016).

The increase in new ocean development presents additional opportunities, especially to developing countries, to harness their ocean resources for hunger and poverty eradication; on the other hand, the expansion of existing uses and the development of new activities pressure the marine environment, which is already experiencing other environmental challenges such as climate change (Sumaila et al., 2019). Therefore, the need to balance development and preserve the ecological status of oceans is paramount.

The need for continued harnessing the ocean to improve livelihoods, whilst preserving the ocean's health, led to the popularisation of the term "blue economy", especially after the United Nations Conference on Sustainable Development of 2012 (United Nations, 2014). Blue economy evolved from the term "green economy," which became popular in 1980 as a means of attaining sustainable development. (Brand, 2012). The blue economy differs from the green economy in that the emphasis is on promoting human wellbeing and social equality in ocean management. As a result, the blue economy emerges as a better choice for ocean management and attaining the United Nations' ocean sustainable development goals. (Roberts and Ali, 2016).

Blue economy has a variety of meanings and applications. This varies by location and organization; nevertheless, there is one common denominator in all blue economy definitions: implementing an integrated ocean management strategy that considers the three pillars of environmental, social, and economic sustainability. (Purvis et al., 2019; Smith-Godfrey, 2016). There are major gaps in how the blue economy components are defined and examined, particularly in connection to the various maritime sectors. (Smith-Godfrey, 2016). Understanding these blue economy sustainability components in the context of the fisheries sector in the Indian Ocean forms the basis of this thesis.

The approach to fisheries sustainability considers the sector as a whole socio-ecological system. The three pillars of ecological, social, and economic sustainability are considered equally in the governance system (Stephenson et al., 2017). Several authors recognise that governance/institution should form the fourth pillar of sustainability as it's a great enabler of ocean management (Stephenson et al., 2017). Globally, achieving this management paradigm has been difficult. Fisheries management regimes are commonly seen to mainly concentrate on ecological assessment, with minimal emphasis on economic and societal evaluations. To a greater extent, the ecological and economic components of fisheries assessment and management continue to dominate. Many stock assessment methodologies and established assessment review and management systems throughout the world are still primarily dominated by, and skewed toward, biological viewpoints and have failed to appropriately incorporate economic, social, and institutional factors(Bond and Morrison-Saunders, 2011). This scenario emerges primarily due to a lack of data, particularly on the environment's economic and social aspects, compared to ecological information, making it challenging to build up economic and social goals with defined targets and realistic indicators(Anderson et al., 2015). Also, the methodologies and tools used to combine ecological, economic, and social variables that successfully negotiate the tradeoff between these opposing aims remain a major problem (Link et al., 2017; Walther and Möllmann, 2014). Given the difficulties of adopting integrated ocean management measures, attempts to understand better the interactions between the pillars of sustainability are critical for allowing effective blue economies(Cisneros-Montemayor et al., 2021).

Conceptual frameworks can be powerful tools for understanding complex socio-ecological interactions such as the blue economy as they are easy to understand (Keen et al., 2018). The conceptual frameworks can aid in the decision-making process by i) helping the stakeholders understand the interaction between the different components of the ecosystem(Mace et al., 2012), ii) Evaluating the outcome of policy decisions(Villamagna et al., 2013) and iii) Communicating the concept of sustainability to non-specialist stakeholders(Potschin-Young et al., 2018). Several conceptual frameworks exist for the blue economy, most of which fit the three-pillar structure. These frameworks have successfully been utilised to understand the blue economy concept in many regions(Bennett et al., 2019; Keen et al., 2018; Okafor-Yarwood et al., 2020). Globally, implementing a sustainable blue economy will be faster if more simple ways of raising awareness and disseminating these integrated approaches are adopted. (Balkema and Pols, 2015; Nagy and Nene, 2021; Voyer et al., 2018a).

This thesis uses the fisheries sustainability framework developed by CFRN to understand fisheries sector challenges in the Indian Ocean Region. Further, we fit the current issues in the fisheries sector into the sustainability framework by mapping them into the four pillars of sustainability. The thesis does not develop a new framework for fisheries sustainability assessment. The thesis employs a case study method to illuminate the four pillars of fisheries sustainable development to create a scenario in which such an approach may be applied to other sectors. The thesis utilises four case studies covering various geographic levels (from local to regional) to achieve its objectives. This thesis may address the gaps in the knowledge of blue economy that exists in the Indian Ocean by highlighting issues and proposing practical ways to overcome these challenges.

1.2 Background

1.2.1 The blue economy

'Blue Economy' is a recent term; its use can be traced to the 2012 UN Conference on Sustainable Development (RIO 2012)(Silver et al., 2015). Before that, 'Green Economy' was used to designate sustainable economies. The green economy is defined as economic development that considers environmental hazards; it focuses on economic growth via more environmentally friendly technology that lessens environmental harm. (Brand, 2012). The green economy has been criticized for being more capitalistic, with greater political-economic interests and less regard for environmental and social concerns (Brand, 2012; Kenis and Lievens, 2015).

Further, the green economy has been inclined toward solving terrestrial environmental issues(Silver et al., 2015). As a result, the transition from a "green" to a "blue" economy was proposed to achieve long-term ocean and inland waterways development and include more social and ecologically sustainable development goals. (Smith-Godfrey, 2016; United Nations, 2014).

The blue economy is defined in a variety of ways; the most prevalent definitions are as follows: 1. "the sustainable use of ocean resources for economic growth, improved livelihoods, and jobs while preserving the health of the ocean ecosystem" (World Bank, 2017), and 2. "ocean economy that aims at "the improvement of human wellbeing and social equity, while significantly reducing environmental risks and ecological scarcities" (United Nations, 2014). The fundamental similarity between the definitions is that for marine areas to be exploited sustainably, ocean economic activities must occur while accounting for potential negative impacts on ocean flora and fauna and human socio-economic growth, such as food security and social wellbeing. (Bennett et al., 2019).

Simply put, the blue economy is a framework that is a multi-disciplinary approach to managing marine sectors that place equal emphasis on ecological, economic, social and institutional sustainability. (Stephenson et al., 2019; Wenhai et al., 2019). Many governments and international organizations have expressed interest in incorporating the blue economy as a framework for long-term ocean management and have made purposeful reforms to include this approach in their policies and programs. The blue economy is strongly matched with the current Sustainable Development Goals 2030, or SDGs, at the global level. It is viewed as a more effective way to address important SDGs, including SDG 14, life below water, SDG 17 partnerships for the goals, SDG 16, peace, justice, strong institutions, and SDG 3, good health and wellbeing. (Lee et al., 2020; Neumann et al., 2017) . The IO member states have shown a strong desire to establish a sustainable blue economy for the area. Members of the Indian Ocean Rim Association IORA resolved to establish a sustainable blue economy in a declaration issued in Jakarta in 2017. The fundamental of the Jakarta declaration heavily relies on the "three pillars" foundation and bring social, economic, and ecological sustainability to ocean management(Indian Ocean Rim Association, 2017). Individual policy solutions from Indian Ocean countries to boost the blue economy are developing. (Colgan, 2018; Hafidh et al., 2021; Purvis, 2015). These efforts have accelerated for countries whose economics are hugely dependent on the ocean, such as Seychelles and Mauritius. Both Seychelles and Mauritius have already developed blue economy policies for their countries(Colgan, 2018).

How feasible is it to develop a blue economy that balances ecological, economic, and social goals? The IO is an excellent place to research this. To begin with, the Indian Ocean is the world's third-biggest ocean basin, with 36 coastline states. This area is home to almost 2.5 billion people, and the majority of the countries are classified as Least Developed Countries (LDCs) (Doyle, 2018a; Voyer et al., 2018b). The social and economic reasons for growing the ocean economy are enormous, as governments strive to improve the lives of their populations. (Llewellyn et al., 2016). Important habitats, such as coral reefs and mangroves, are found in the region, posing a threat of environmental damage resulting from blue economy expansion. (Doyle, 2018a). The IO region is home to 30% of the world's coral reefs. Its diverse ocean environment supports various maritime activities such as fishing, accounting for around 15% of wild-caught fish globally. Here, sustainable exploitation of marine resources is critical to the ocean's ability to provide ecosystem services to the inhabitants continuously. The blue economy provides a key framework and strategic advice for Ocean management in the IO countries.

1.2.2 Ocean sustainability

In 1980, when worries about over-exploitation of natural resources developed and action was necessary, the word "sustainability" in natural resource management became widespread. Depending on the focus of the resource being managed, different sectors interpret the word differently; for example, in fisheries management, sustainability is described as "management that guarantees utilization of the stock while conserving the renewable stock (Tivy and O'Hare, 1981). Sustainable development, according to the Brundtland Commission report, is "development that fulfils current demands without jeopardizing future generations' ability to satisfy their own needs. (Brundtland and Khalid, 1987). The original definitions of sustainability vary, but the unifying idea was using resources while considering the supply for future generations. These older definitions were criticised mainly because they were more concerned with the environmental concerns of resource extraction. Political, economic, and cultural elements of natural resource management have been mentioned as equally important and must be considered if sustainability is accomplished. (Brand, 2012). As a result, modern sustainability methods have turned to more comprehensive definitions of sustainability that embrace the whole range of the social-ecological systems. (Jones and Stephenson, 2019).

There is still no single definition of sustainability; most definitions agree that sustainability should be grounded in four pillars, namely ecology, economics, social and institutional, which interact to provide a more comprehensive approach to sustainability(Boyer et al., 2016; Hansmann et al., 2012; Purvis et al., 2019). Ocean managers agree that the blue economy's sustainability can only be realized if the four pillars are balanced (Bennett et al., 2019; Cisneros-Montemayor et al., 2021). While most people agree on this, there are obstacles to integrating the four pillars of sustainability in ocean development, with a greater focus on ocean development being put on economic and social elements while disregarding the environmental impacts of this development (Rindorf et al., 2017). Therefore, a greater understanding of the importance of all the ocean sustainability pillars is required to propagate sustainable ocean management.

1.2.3 Sustainable Fisheries Sector

Fisheries globally are experiencing a problem maintaining sustainability as declining fishing stocks characterise most regions (Pauly et al., 2002; Worm et al., 2009). Management interventions are essential to manage and strengthen the sector, particularly since more issues from ocean developments, such as overfishing, pollution and climate change challenges, are anticipated. (Cohen et al., 2019; Costello et al., 2016; Gaines et al., 2018). Following the UN's focus on including ecological, social, and economic aspects of sustainability in marine management, most ocean and fisheries management techniques were established using integrated approaches. Ecosystem-based fisheries management (EBFM) (Aburto et al., 2012), the fisheries-specific Ecosystem Approach to Fisheries (EAF) (FAO, 2003; Link, 2002), and Integrated coastal zone management (ICZM) (Post and Lundin, 1996) are examples of such Integrated fisheries management techniques. All integrated fisheries management techniques are built on the same principles of sustainable development, with a primary emphasis on the three pillars of economic, social, and ecological consideration. Implementing this integrated management, which employs the three-dimensional framework for sustainable fisheries sector management, remains a significant problem. A fourth pillar (institutional/governance) has been proposed in recent research on sustainable fisheries management (or governance). Following the work of Stephenson et al. (2018), this thesis will consider fisheries sustainability as having four dimensions: ecological, economic, social, and institutional. As the fourth pillar in the fisheries sector's sustainability, governance is viewed as an enabler for the three other dimensions (Garcia et al., 2000; Kurien, 2015; Stephenson et al., 2018).

1.3 Research Objectives

Pressure on marine ecosystems is growing in IO due to the increase in ocean-based developments. This thesis aims to support a greater understanding of these pressures on the different aspects of sustainability by utilizing a sustainability framework and fitting issues identified from case studies.

First, the focus is placed on understanding the issues in fisheries from three different case studies presented in different publications. Case studies 1-3 and the issues identified from the case study are mapped into the CFRN fisheries sustainability framework proposed by the Canadian Fisheries Research Network. The second aim is to provide practical solutions to fisheries sustainability from a case study 4. The final aim was to project the findings on challenges and opportunities for sustainable fisheries into the larger blue economy.

The main thesis questions addressed are;

RQ1; What is the spatial distribution of the six billfish species and the potential threat from commercial fishing in the IO.

The first research question deals with the first case study where we use the billfish fishery as a case study to shed light on the sustainability ecological dimension in the IO.

RQ2: What are the impacts of port development on small-scale fisheries in the East Africa region.

The second research question deals with the second case study where we use port development to illuminate socio-economic issues facing small scale fisheries (SSF) in the East Africa region of the IO.

RQ3: What is the Extent of commercial fishers' unreported fishing activity in the IO, and Is there a role for governance in IUU prevention?

The third research question deals with the third case study, where we use the unreporting of commercial fishing activities in the IO to illuminate the economic dimension of sustainability.

RQ4. Can combining automatic identification system (AIS) and the vessel monitoring system (VMS) data sources address data gaps on fisheries for marine spatial planning

The fourth research question relates to the second objective. We investigate the viability of merging AIS and VMS datasets to solve the challenge of fisheries' spatial data scarcity for management in the region.

Chapter 2. Research Design and Methodologies

2.1 Study area

This study covers the Indian Ocean (IO) within 15^0N to 40^0 S, 20^0E to 121^0 E (Figure 2.1.1). The Indian Ocean is the world's third-largest ocean, bordering 36 nations and 2.7 billion people with huge economic and socio-cultural disparities. (Doyle, 2018a; Techera, 2020a; Voyer et al., 2018b). Fishing is one of the region's most important marine activities. In 2018, the region supplied over 15% of the world's wild-caught marine fish. (FAO, 2020). Small-scale fishers are prominent in coastal areas, providing food and livelihood to the local population(FAO, 2020; Techera, 2020b).

Even though fish catches are increasing in the region, poor fisheries management is a significant problem, with 31% of the region's fish populations exploited at ecologically unsustainable levels. (FAO, 2020). Due to its broad Area Beyond National Jurisdictions (ABNJ), the region draws numerous international commercial fishing vessels. (Crespo et al., 2018a). Illegal, unreported, and unregulated (IUU) fishing poses a severe danger to vulnerable species in the ABNJ due to a lack of monitoring. (Riskas et al., 2018).

Because of its distinctive geomorphological characteristics, including plateaus, ridges, and seamounts, the IO has high biodiversity and occurrence of endemic species, making it one of the most diverse ocean basins globally. (Obura et al., 2012; Warner et al., 2012). The climate and current flow and the distribution of species in the area are primarily influenced by the seasonal monsoon system and the region's geomorphological features. (Obura et al., 2012; Schott and McCreary Jr, 2001a). The western IO is exceptionally rich in coral biodiversity; it contains 16 % of the global coral reefs. (Obura et al., 2017). The eastern part of the Indian Ocean is also rich in biodiversity, particularly mangroves, corals, and seagrass meadows. Indonesia alone hosts more than 20% of the world's mangrove area (Murdiyarso et al., 2015; Sidik et al., 2018).

According to recent estimates, 95 % of persons involved in fisheries-related activities in the globe originate from Africa and Asia (with the Indian Ocean Rim accounting for the majority) and are dominated mainly by SSF. (FAO, 2020). Despite the SSF's enormous contribution to the socioeconomic elements of the region's coastal residents, the sector is often disregarded. SSF confronts several obstacles, including access to fishing grounds. (Thoya and Daw, 2019), reduced harvests owing to overfishing and deteriorated ecosystems (Jackson et al., 2001), poor fish market (Wamukota, 2009), conflicts with other maritime sectors (Mwatha, 2002; Rodden, 2014)

Many IO countries have recently gained interest in expanding the blue economy (Doyle, 2018a). Some of the proposed projects under the blue economy are likely to impact fisheries. An example is the expansion of Marine traffic activities by constructing new ports in Lamu and Shimoni ports in Kenya and Bagamoyo Port in Tanzania (described in detail in case study 2). The increase in ocean activities is likely to increase pressure on the marine ecosystem and potentially compromise fisheries' sustainability.

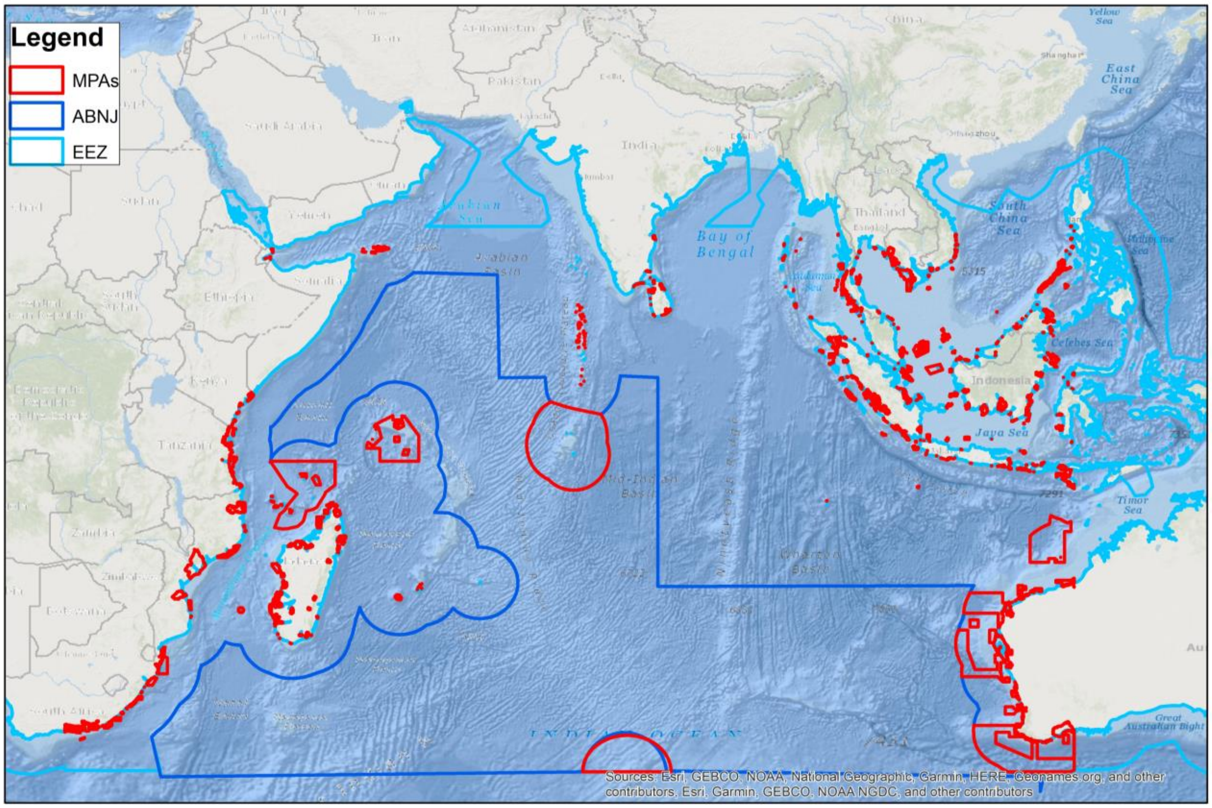

Figure 2.1.1: Map of the IO showing current management regimes Marine protected areas, Exclusive economic zone and Areas beyond national jurisdiction.

2.2 Study Method

2.2.1 Case study approach

The case study approach was seen as an appropriate method for this study as it is one of the valid methods for qualitative research (Baskarada, 2014). The case study approach is an excellent option for studying data-poor areas where combined approaches such as observation, interviews and documents could collectively be used to build new theories (Eisenhardt, 1989). The study comprises four case studies from the fisheries that focus on the social, economic, and ecological sustainability aspects sector.

The first case study focuses on the distribution of billfish in the Indian Ocean region to emphasise the ecological aspect of sustainability. Billfish are essential fisheries in the IO ocean because they are fished by small-scale, recreational, and commercial fishermen. Half of the billfish species are now exploited at levels over their biologically viable limits, making them a great case study for tying endangered species to blue economy growth. (IOTC, 2019).

The influence of port expansion on small-scale fisheries is the subject of the second case study. Using experiences from port development in Kenya and Tanzania, this empirical research sheds light on the potential implications of ocean development on fisheries. The goal of the case study is to provide light on the social dimensions of long-term fisheries sustainability.

Illegal fishing by foreign vessels in the region is the subject of the third case study. The economic losses to the fisheries sector because of unreported fishing operations are highlighted in this empirical research. This case study aims to shed light on the economic side of sustainability.

"AIS and VMS Ensemble Can Address Data Gaps on Fisheries for Marine Spatial Planning," the fourth case study, is an example of a realistic solution to the IO region's fisheries sustainability problems.

2.2.2 A framework for fisheries sector sustainability

The thesis's ultimate purpose is to demonstrate how the concept of sustainability might aid in the advancement of blue economy efforts in the IO region. To simplify this, we use the fisheries as an example and place the issue that arises from case studies into a fisheries sustainability framework. This framework serves several purposes, including as a basis for identifying alternate management objectives, a framework for scenario comparison, a report card for fisheries plans, and a practical implementation of integrated fisheries management. We utilise the framework by

Stephenson et al. 2018, which evaluated fisheries sustainability based on the four dimensions of sustainability: ecological, social, economic, and institutional (Figure 2.2.1).

Mapping fisheries challenges emerging from the case studies to this framework was done by first compiling a list of issues arising from each case study. These were then compared and matched with the comprehensive list of elements (Stephenson et al., 2018).

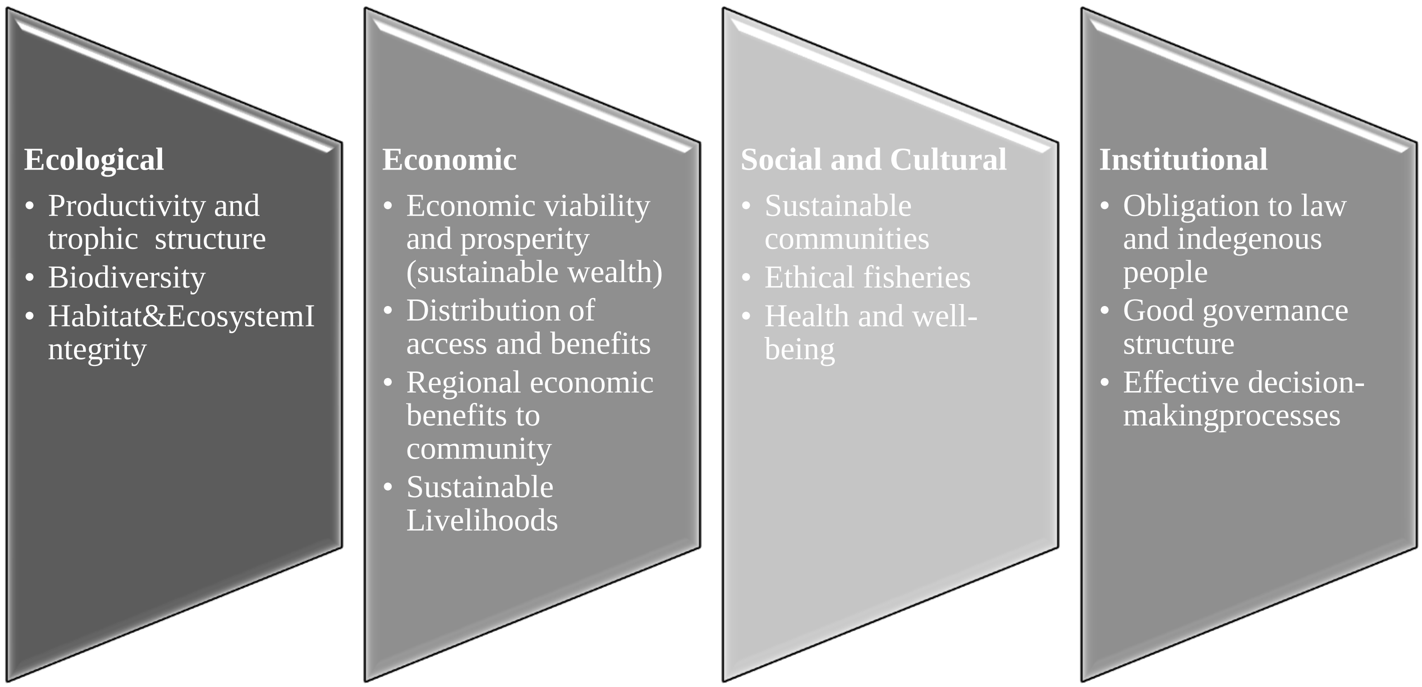

Figure 2:2.1 representation of the Four fisheries sustainability dimension and Key objectives for each pillar, used as guidance for issue identification and mapping, adapted from Stephenson et al., 2018.

Chapter 3. Case Studies

3.1 Case study 1. Environmental controls of billfish species in the Indian Ocean and implications for their management and conservation.

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Keywords: bycatch, ensemble modelling, fishing pressure, niche overlaps, spatial ecology, species distribution modelling,

Abstract

Background and aim: Billfish are epipelagic marine predators facing increasing pressures such as overfishing and rising global temperatures. Overfishing is a major concern, as they are caught by industrial longline fishers targeting tuna. Billfish are targeted by multiple fishing sectors, which provides food, socio-economic and cultural benefits. To support effective billfish management and conservation, it is essential to understand their spatial distribution and the environmental factors that may influence it.

Location: The focus of this study is the Indian Ocean (IO), where there are gaps in understanding the interactions between fisheries and billfish distribution. Three out of six billfish species are at risk from overfishing. Therefore, determining their distribution is crucial to their management and conservation.

Methods: Using Ocean Biogeographic Information System (OBIS) occurrence data, Indian Ocean Tuna Commission (IOTC) catch data, and environmental covariates, we applied species distribution models to investigate the spatial extent of the realised niches of six billfish species in the IO. We also determined the role and relative importance of environmental drivers. Moreover, we evaluated the association between species' spatial distribution and the fishing effort distribution.

Results: We found niche partitioning and overlap among the six species identified spatial distribution, with higher species richness in the northern region of the IO and off the East coast of Africa. Temperature, mixed layer depth and salinity were identified as the most important predictors of species distribution, with moderately warm and stable environments preferred by most billfish species. Areas with high species richness and high fishing effort overlap were primarily found in the Areas Beyond National Jurisdiction (ABNJ). In contrast, areas with high species diversity richness and low fishing effort were found mainly in the Exclusive Economic Zone (EEZ).

Main conclusion: Spatial overlap between fishing effort and billfish projected distribution suggests inadvertent fishing pressure on billfish populations as they are caught together with targeted tuna. Spatial distribution transcends maritime zones, reinforcing a need to formulate effective management policies for marine areas beyond national jurisdictions.

Introduction

Billfish are epipelagic predators distributed widely throughout the tropical, subtropical and temperate waters of the world's oceans (Nakamura, 1985; Reygondeau et al., 2012; Restrepo et al., 2016). The Indian Ocean (IO) is home to six species of billfish, including the black marlin (Istiompax indica), sailfish (Istiophorus platypterus), striped marlin (Kajikia audax), blue marlin (Makaira nigricans), short bill spearfish (Tetrapturus angustirostris) and swordfish (Xiphias gladius). These species are targeted by multiple fishing sectors, including small-scale, commercial and recreational fishers for food, socio-economic and cultural benefits (Doyle, 2018b; Kadagi et al., 2021b; Techera, 2020b). Despite their significance, billfish are currently facing environmental pressures and overexploitation, threatening their sustainability of fisheries (Dell'Apa et al., 2018; Juan-Jordá et al., 2011; McIlgorm, 2010).

Historical trends suggest that global billfish catches increased steadily from 1950 to 2000 but have declined recently in other oceans except for the IO, where reported catch has been rising (Pons et al., 2017; Sharma et al., 2018). The exploitation status of billfish species differs among the three major oceans. For instance, In the Atlantic Ocean, approximately over 70% of the billfish populations are considered overfished or undergoing overfishing, compared to the Pacific and IO, where 62% and 50% of the populations are overfished or undergoing overfishing, respectively (IOTC, 2020a; Restrepo et al., 2016). However, a disproportionate effort is expended towards billfish studies among ocean basins. In the IO, gaps still exist in understanding the interactions between fisheries and billfish distribution in space and time, which is necessary for informing their conservation measures.

Recent stock assessments of IO billfish species reported that the black marlin, blue marlin and striped marlin are overfished, while sailfish are undergoing overfishing (Andrade, 2016; IOTC, 2020a; Yokoi and Nishida, 2016). The stock status of the shortbill spearfish remains unknown due to limited data, while the swordfish stocks are not subject to overfishing (IOTC, 2020a). Here, management recommendations are often entirely dependent on aggregated catch and effort trends, with less consideration of the spatial distribution of billfish and associated factors. This may be particularly problematic as climate-driven pressures influence environmental conditions that determine habitat use of billfish species, with implications for their exploitation and conservation (Dell'Apa et al., 2018). Therefore, besides monitoring fish stocks and fishing efforts, there is a need to understand the relative role and potential impacts of environmental pressures such as increased water temperature on billfish distribution to inform conservation and management decisions at national and oceanic scales.

Environmental factors are known to influence billfish movements and foraging habits, and several studies globally have described the strong relationships between their distribution and environmental covariates such as temperature, oxygen, and salinity (Block, Booth, & Carey, 1992; Block et al., 1992; Boyce, 2004; Carlisle et al., 2017). Studies on billfish distribution indicate spatially distinct niche preferences based on physiological requirements (Lam et al., 2015; Ricklefs et al., 2014; Shimose et al., 2010). Understanding correlations between billfish distributions and environmental variables may help determine their niche preferences, including potential niche overlaps (Boyce, 2004; Boyce, Tittensor, & Worm, 2008; Reygondeau et al., 2012). When coupled with stock assessments, such information is critical in developing spatio-temporal management and conservation measures (Boerder et al., 2019; Carlisle et al., 2017; Hazin and Erzini, 2008; Sedberry and Loefer, 2001). However, a lack of information on environmental controls, niche distribution, and overlaps of billfish species in the IO hinders the ability to advance their spatio-temporal management.

Common approaches to delineating the distribution of species involve using species distribution models (SDMs) that require presence and absence data and environmental covariates to predict habitat use of species. SDMs have been used widely to characterise the niches of highly migratory species such as birds and seals(Elith and Leathwick, 2009; Raymond et al., 2015; Scales et al., 2016). SDMs can address challenges related to data deficiency for species requiring management intervention by modelling distributions and identifying potential interactions with threats such as fishing activities (Escalante et al., 2013; Queiroz et al., 2016).

Here, we addressed critical knowledge gaps on the effects of environmental controls on billfish in the IO. First, we used SDMs to investigate the spatial distribution and niche partitioning of each of the six billfish species. Second, we evaluated environmental covariates' role and relative importance in predicting the identified Spatial distribution. Finally, we examined the potential risk of commercial fishing to billfish stocks by estimating the overlap between the projected billfish distributions and fishing activity. The results of our study will enhance the understanding of critical environmental controls their influence on the distribution of billfish species and contribute to sustainable management efforts.

2. Data and Methods

2.1 Data

From the Ocean Biodiversity Information System (OBIS) database (www.obis.org), we collected 2314 occurrence records for black marlin, sailfish, striped marlin, blue marlin, shortbill spearfish, and swordfish across the IO (Table S1). The OBIS database contains species occurrence data harmonised from multiple sources and quality checked (Costello et al., 2007; Klein et al., 2019). The occurrence records in the OBIS database for billfishes in the IO primarily comprises data from commercial fishery logbooks and/or observer programmes. Occurrence records from the OBIS database have previously been utilised to estimate species distributions in other regions (Coro et al., 2016; Jensen et al., 2017). On closer examination of OBIS records within our region of interest, we found data gaps and geographical bias in the occurrences due to underreporting billfish data and little fishing effort in some areas. Consequently, we processed and used fisheries catch data from IOTC to fill the data gaps.

Fisheries data containing nominal effort (number of hooks) and catches (number of fish) were obtained from the IOTC database (https://iotc.org/data/datasets). These data are reported to IOTC in a gridded format at $1^{\circ} \times 1^{\circ}$ and $5^{\circ} \times 5^{\circ}$ by day, month, year, and grid, based on countries' reports for their vessels operating in the region. We extracted longline catch data from 2008 to 2018 for the IO region and re-gridded it onto a $1^{\circ} \times 1^{\circ}$ grid for consistency. We used longline catch data because longline vessels accounted for approximately 70% of historical total billfish catches reported to IOTC from the 1990s up to the early 2000s (IOTC, 2020b). Over the past few years, longline vessels have caught a smaller share of total billfish, up to 30% in 2018, with offshore gillnet fleets playing an increasingly important role. However, longline data is more readily accessible, as many countries operating in the IOTC region do not report most of their billfish catches from gillnets.

For a merged IOTC and OBIS occurrence dataset, we first created IOTC occurrence points in all $1^{\circ}\times1^{\circ}$ grid areas where IOTC catches were reported. Using the OBIS occurrence points, we removed all IOTC points that occurred over a known OBIS point. The IOTC spatial data does not undergo the same quality checks as the OBIS database. Therefore, to increase the certainty of the occurrence, we only considered IOTC grids with the highest catch (>=50% quantile) as occurrence points.

2.2 Environmental data and physiological mechanisms

The distribution and abundance of marine fishes are highly dependent on physiological mechanisms (Jørgensen et al., 2012). Using existing hypotheses of environmental influence on billfish physiology, we identified covariates that best represent the environmental cause of physiological significance. Several environmental variables have been found to influence billfish habitat preference and distribution (Carlisle et al., 2017; Lam et al., 2015; Sedberry and Loefer, 2001). These include seawater temperature, mixed layer depth (MLD), productivity, sea surface height (SSH), depth and salinity.

Temperature and salinity affect billfish physiological processes such as metabolic rate(Carlisle et al., 2017; Neilson et al., 2009; Reygondeau et al., 2012; Rooker et al., 2012). Ocean productivity indicates the availability of food for small fish preyed upon by billfish. The Chl-a level offers information on an area's primary production(Sedberry and Loefer, 2001; Seki et al., 2002). The billfish's vertical movements, food availability, and oxygen levels are influenced by depth. The amount of light required for primary production is lower in deeper areas, and thermoclines may impede oxygen circulation (Block et al., 1992; Carlisle et al., 2017). MLD is a measure of how well surface waters mix with deeper water due to temperature differences, and it can influence billfish vertical movement (Lam et al., 2015; Williams et al., 2017). SSH denotes oceanic features such as gyres, eddies, and upwelling areas that influence MLD and primary productivity.

The appropriate covariates for use in the SDMs were derived from the above hypothesis (Table S2). We obtained the covariates' respective time series (2010-2020) data from the Global Ocean Physical Reanalysis and Global Ocean Biogeochemistry hindcast on the Copernicus website (http://marine.copernicus.eu/services-portfolio/access-to-products/). Monthly time series data were aggregated into long term averages and coefficients of variation (CV).

2.3 Data analysis

Billfish niche partitioning

We investigated billfish niche partitioning, and the mechanisms influencing their niche using SDMs implemented using R x64, 4.1.0 (R Core Team, 2021) package sdm (Naimi & Araujo, 2016). Before fitting SDMs, we tested the occurrence data for geographical and sampling biases using the R package Sampbias (Zizka et al., 2020). We also tested for multicollinearity among the environmental covariates by applying variance inflation factor (VIF) tests using the usdm R package (Babak Naimi, 2015). VIF values of <3 indicate that multicollinearity is not a serious concern. However, because our objective was to compare relative importance among the covariates, we applied a more conservative VIF threshold of 1.5.

To fit SDMs, we used presence-only records as the response variable against six environmental covariates. Most SDMs require both presence and true absence datasets. Because our occurrence data lacked true absence records, we used the method "gRandom" in the sdm package to generate a set of pseudo-absence records for each species that matched the number of the presence points (Naimi & Araujo, 2016). The algorithm uses environmental spatial data layers and the presence points to model suitable areas for the species. It randomly selects locations least ideal for the species as pseudo-absence points. Matching points are then removed to verify that no pseudo-absence is placed over a known presence point(Barbet-Massin et al., 2012; Senay et al., 2013).

We accounted for the strengths and weaknesses of different SDM approaches, including regression-based models and tree-based machine learning approaches. Four algorithms were run by applying ensemble modelling: Generalised Linear Models (GLMs), Generalised Additive modelling (GAMs), Gradient Boosting Machines (GBMs), and Random Forests (RFs). All models were run using the following settings, replicatin='sub', test.percent=30,n=10 (evaluates using 10 runs of subsampling replications taking 30 per cent as a test) (Naimi & Araujo, 2016). The RF algorithm has 'hyper-parameters', which are not estimated from the data (unlike parameters of a statistical model) and are set by the user to influence model performance. The number of trees (ntree) and the number of random samplings from the set of predictors (mtry) are the most influential for the RF models are (Probst et al., 2019). To determine a combination of mtry (1-10) and ntree (1-500) that produced the best performance for each of the alternative models, we used the caret package in R (Kuhn et al., 2020). We then ran the models using the identified parameters. GAMs and GLMs were fitted using binomial error distributions with logit link function, while GBMs were fitted using Bernoulli distributions and default hyperparameters values in sdm.

We evaluated model performance using the "true skill statistic" (TSS) that measures the model performance based on sensitivity and specificity (Allouche et al., 2006). Before predicting each of the four models spatially over the IO, we confirmed that ranges of predictor variables in the sampled area were comparable to that of the study area's background data to avoid model extrapolation. To obtain a harmonised prediction for each of the six species, we generated model ensembles based on the weighted mean by the model performance of the four models(Garcia et al., 2012; Grenouillet et al., 2011; Jensen et al., 2017; Scales et al., 2016; Zanardo et al., 2017).

Temperatures and MLD experience seasonal variations in the IO (Keerthi et al., 2016). Testing for seasonality in species distribution models is complicated by a lack of data on seasonal observations. Environmental variability metrics are often used as proxies for seasonality in SDMs.

For example, standard deviation (Bazzato et al., 2021), the difference between the temperature of the warmest and coldest month as a proxy for seasonality (Jarvie and Svenning, 2018; Tyberghein et al., 2012), and coefficient of variation (Porfirio et al., 2014) can be used as proxies for seasonality in SDMs. Here we used the CV to infer seasonality. To evaluate the potential influence of seasonality on the species' spatial distributions, we plotted the probabilities of occurrence against CVs for temperature and MLD. This essentially created a bivariate occurrence space illustrating the association (or lack of) between seasonality and distribution. Finally, the predicted habitat suitability was converted to presence-absence using the highest kappa threshold (Liu et al., 2016).

b) Niche overlap

To evaluate overlap in the billfish niches', we applied the 'niche overlap' function in the r package DISMO (Hijmans, Phillips, Leathwick, Elith, & Hijmans, 2017; Warren, Glor, & Turelli, 2008). The niches rasters were stacked to create a billfish species richness map.

c) Spatial congruence between billfish distribution and longline fishing

We evaluated the spatial congruence between species richness and the Global Fishing Watch data (GFW) derived effort distribution. GFW computes the global distribution of fishing effort using the location data of fishing vessels obtained from the Automatic Identification System (AIS). GFW retrieves the location data of the fishing vessels and maps the fishing effort (hours) distribution at a resolution of a 10km grid (Guiet et al., 2019). We retrieved daily global data in spreadsheets to obtain annual GFW effort estimates for the IO. This was done by first obtaining the total fishing effort for 1◦×1◦ grid for each year. The average for all the years was obtained by summing the annual total fishing effort, divided by years. These were subsequently mapped into 1◦×1◦ grid and clipped to the IO extent.

The spatial interaction between billfish species and fishing effort was calculated by first dividing the fishing effort and species layers into two categories: low (less than 50 percent quantile) and high (greater than 50 percent quantile). The two layers were then intersected to provide four interaction categories: low species-low fishing, low species-high fishing, high species-low fishing, and high species-high fishing.

Data and methodological approach sensitivity test.

The outcome of SDMs is as good as the data and the algorithms used. We opportunistically used a different dataset version and alternate algorithm to function as a sensitivity test to our methodological approach. In this second approach, we create a dataset with absence points instead of the pseudo-absence points method used in the first approach. Since the presence data used is primarily from longline vessels that target swordfish, we generate the absence data of all the other species by comparing them with the swordfish presence data. Each species' presence data was matched with the swordfish presence points. In cases where there was no overlap between the species' presence and swordfish presence, the swordfish presence point was considered absent points for the species. This was similar to the approach used by Torreblanca et al. (2019). We then compared the projected realised niches for each species using the niche overlap' function in the r package DISMO to dictate possible differences between the two approaches.

Results

3.1 Billfish niche partitioning

There was clear niche partitioning among the six billfish species. For most species, the projected spatial distributions are centred in Western IO, Northern IO, and western Australia (Fig.1a-f). There were differences and similarities in the individual species' niches. Black marlin and striped marlin had the highest niche overlap index (0.85). In contrast, the species with the least potential for niche overlap were the blue marlin and shortbill spearfish, with a niche overlap index of 0.25. (Fig. 2).

Striped marlin had the largest projected distribution, with the projected realised niche occurring in the Western IO, Northern IO, and western Australia (Fig. 1a). The least distributed species is the shortbill spearfish, with a projected niche occurring mainly in the south-western IO and western Australia (Fig.1f). Our findings also show that marlins had similar projected niches compared to the other species, which corresponds to the IOTC stock status, as all three marlin species are overfished in the region, while species that had contrasting projected niches, such as the swordfish, having better stock status (Fig. 2).

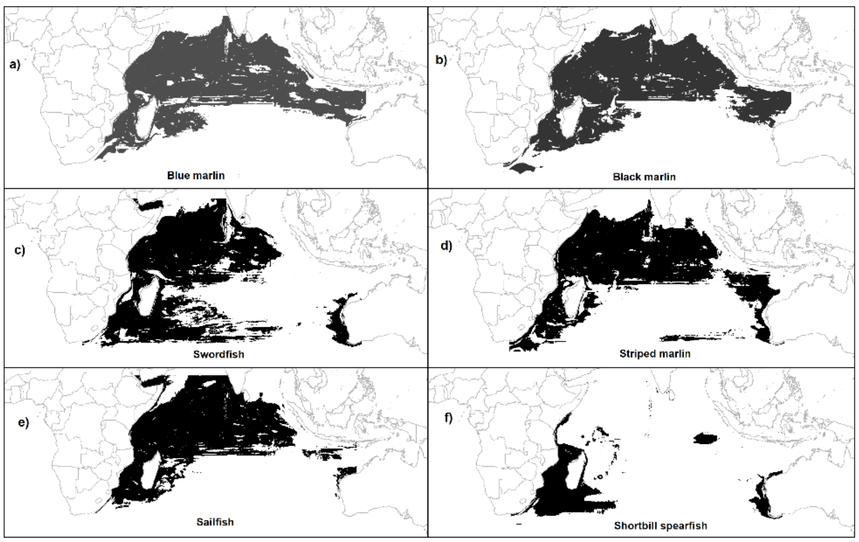

Figure 3.1.1: Projected current distributions for billfish species in the Indian Ocean. The maps show the areas that are more suitable for each species. Projected distributions result from converting the habitat suitability to 0 and 1 (black) by applying a threshold where kappa is maximised. The initial suitability maps are shown in the supplementary material (S3). Projected distributions are ordered from the largest to the smallest.

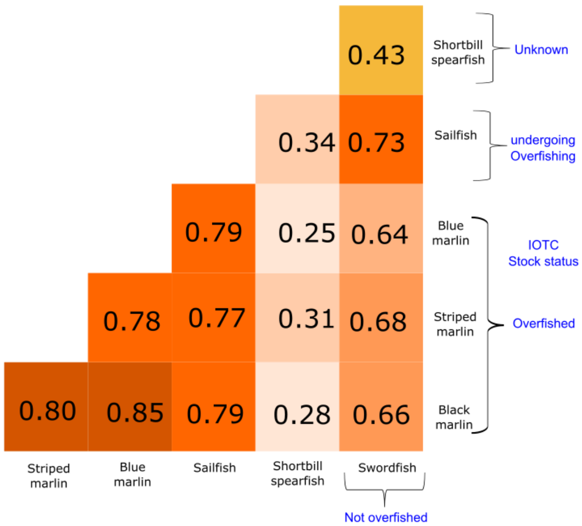

Figure 3.1.2: Tests of niche overlap among the six billfish taxa, with 0 and 1 representing no overlap and perfect overlap, respectively. Taxa stock assessments are also illustrated based on the recent IOTC report (IOTC, 2019; Yokoi and Nishida, 2016; Andrade, 2016).

3.2 Role and relative importance of environmental covariates

There were agreements among model types on variable importance for most species, except for salinity, which was indicated as important in GLM models and not in the other three (GAM, GBM and RF) (Table S6). Temperature, MLD, and salinity were the most important variables in predicting distribution in all species across all the model types but with a species-specific difference in relative importance. For example, temperature and salinity were the most important predictors for black marlin, blue marlin, and sailfish. Similarly, MLD and salinity were the most important predictors of striped marlin and swordfish occurrences (Fig. 3)

The average temperature was positively associated with the occurrence of all species, with an optimal mean range of between 22 and 30 ^{o}C (Fig. 4a). Our results show that swordfish has the largest temperature tolerance ranging between 18 and 30 ^{o}C, while sailfish was predicted to occur within a narrow mean temperature range of 23 and 29^{o}C (Figure 3.1.4a, S3.1.4). A high probability of occurrence was associated with low MLD and optimal MLD values of 20 and 40m (4d). For salinity, GLM, GBM, and RF models revealed a similar trend of increasing probabilities between the range of 32 and 36psu (4b). Although depth was less important in influencing the distributions of some species, swordfish and shortbill spearfish showed a stronger positive association with depth with decreasing probabilities of occurrence in shallower depth (Fig. 4c).

The distribution ranges for temperature, MLD, salinity and depth varied among the species (Fig. 4). The species with the highest depth ranges were shortbill spearfish (-1542 to -4756), while the striped marlin showed the narrowest depth range (-2773 to -5081) (Fig. 4c). Areas with the highest suitability of finding swordfish also had the greatest MLD range (19 and 33m). In contrast, sailfish displayed the smallest MLD ranges with the highest probability between mean MLD values of 7 and 32m (Fig. 4d).

Our results show relationships between the spatial distribution of the species and seasonal changes in temperature and MLD. The species distribution fall in regions with a low CV in mean temperature and a higher MLD CV, especially for the marlins and sailfish (Fig 5). Swordfish and shortbill spearfish did not exhibit clear seasonality effect on their niche distributions.

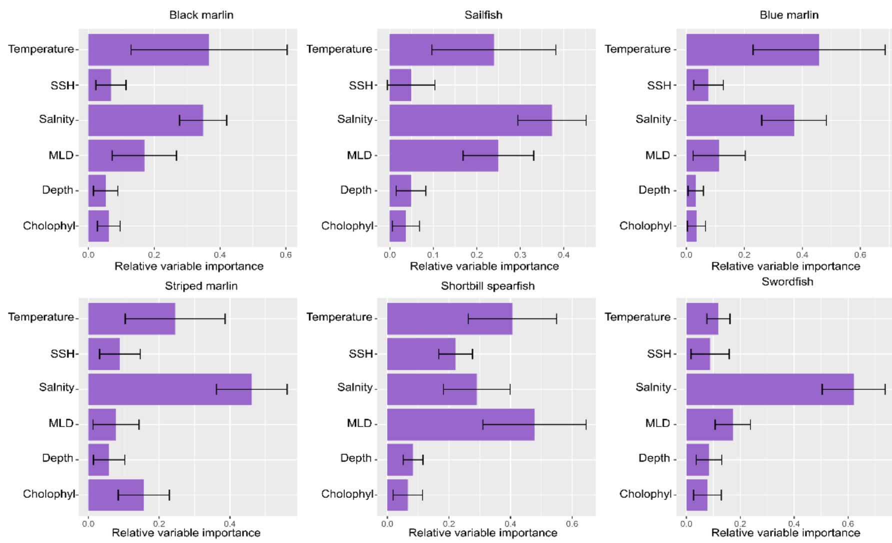

Figure 3.1.3: Relative importance of predictor variables used for predicting billfish species in the Indian Ocean.

The relative importance compares the importance of a variable in a model with the other variables in the same model and ranges from 1 to 0). Relative variable importance is based on pearson correlation coefficients weighted by AUC values of contributing models.

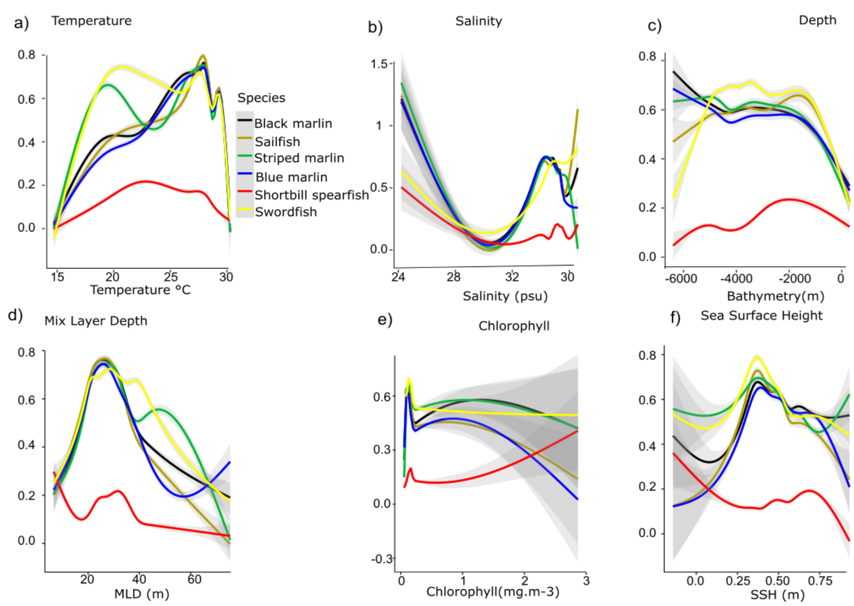

Figure 3.1.4: Response curves showing the effects of the predictor variables on billfish species' probability of occurrence. Environmental variables are plotted on the X-axis, and the Y-axis represent habitat suitability.

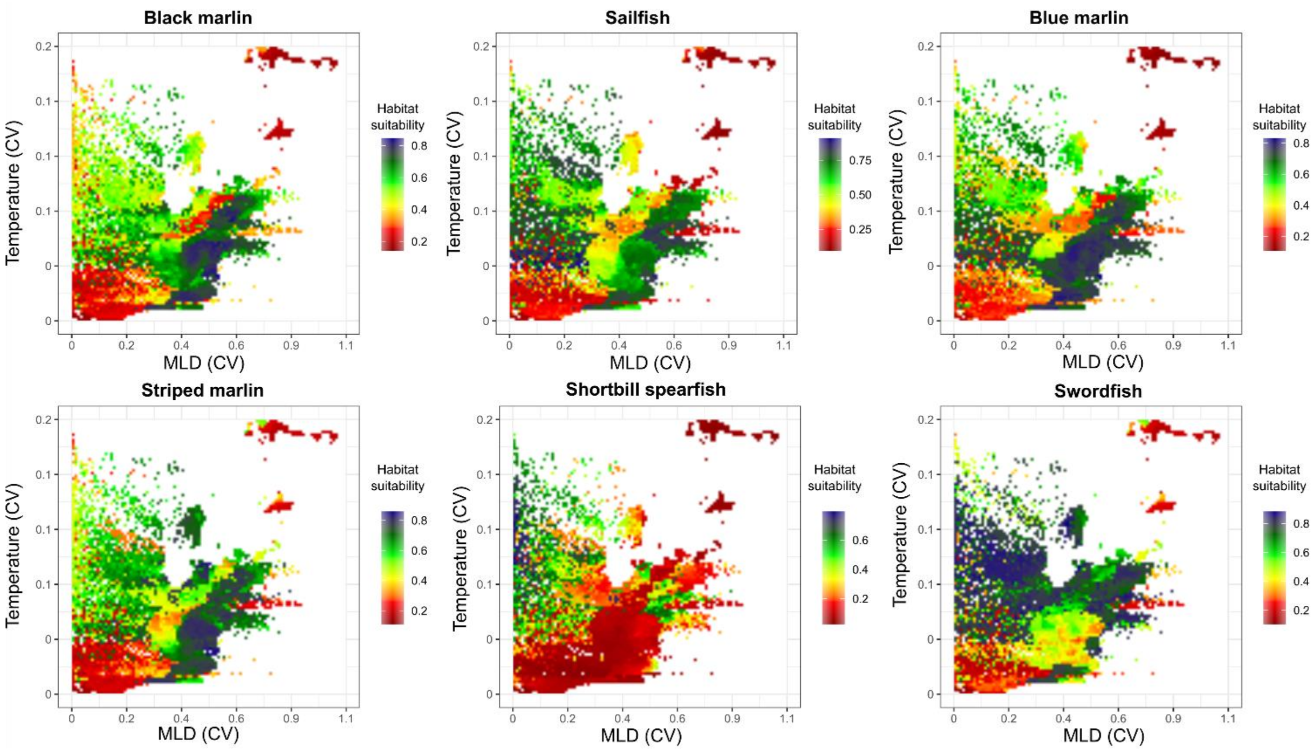

Figure 3.1.5: Habitat suitability for six billfish species is visualised against axes of MLD and temperate coefficients of variation, used as measures of seasonality across the IO.

3.3 Fishing effort interaction within billfish spatial distributions s

We found species richness hotspots (high niche overlap) for the six billfish species off the eastern coast of Africa, the northern region of the IO, and Australia's western coast. In contrast, the southern IO is characterised by fewer billfish species (Fig. 6a). Areas with many billfish species present were also found to experience high fishing pressure.

The EEZ and the high seas are essential areas for billfish, with 55% of the billfish spatial distributions found in the EEZ of the IO nations, while 45% were found in the high seas. Areas with a high probability of occurrence for most species and high fishing effort overlap were primarily found in the Areas Beyond National Jurisdiction (ABNJ). In contrast, areas with high species diversity and low fishing effort were found mainly in EEZ (Fig.,6b,7a). The areas with the highest predicted occurrences of billfish also varied among countries, with some countries in the Western Indian Ocean (WIO) such as Mozambique, Seychelles, Madagascar, and Mauritius being "hot spots" for species occurrence (Figure 3.1.6a, 3.1.7b).

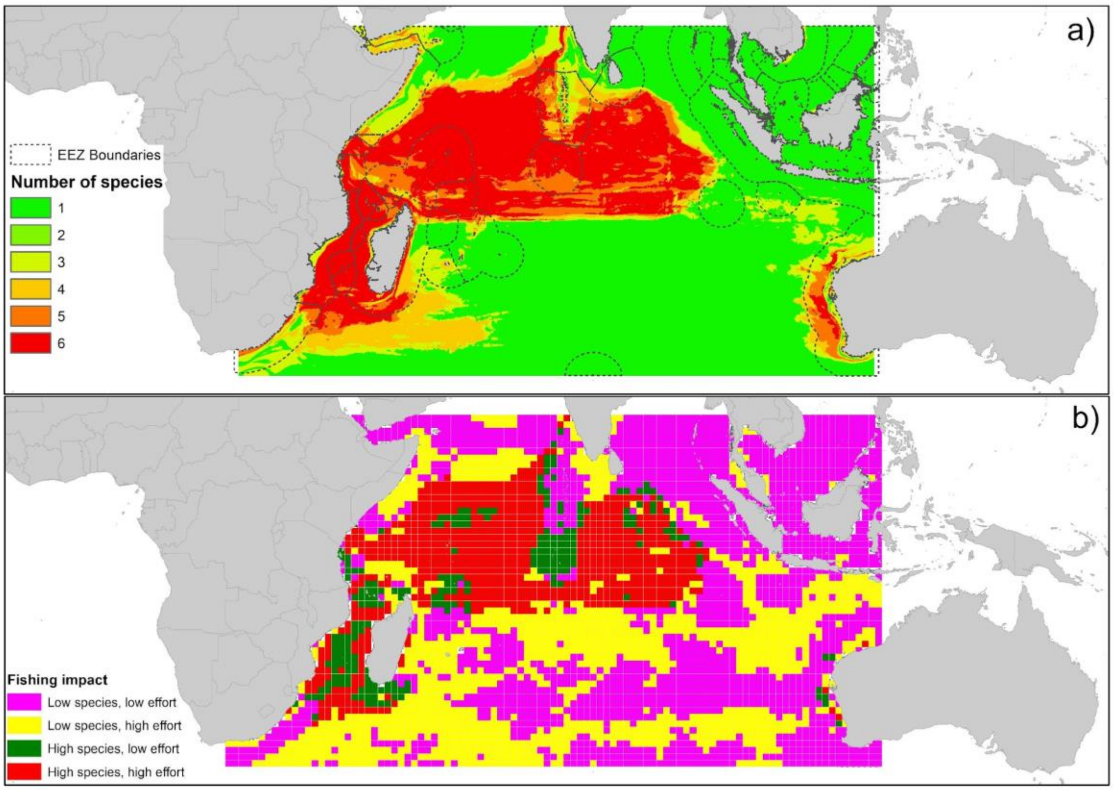

Figure 3.1. 6: a) Distribution map of the six billfish species showing the extent of overlapping distributions and the EEZ boundaries (b). Species richness across a gradient of fishing effort, Areas with a high ((>50% quantile) number of species had a higher (>50% quantile) mean monthly fishing effort.

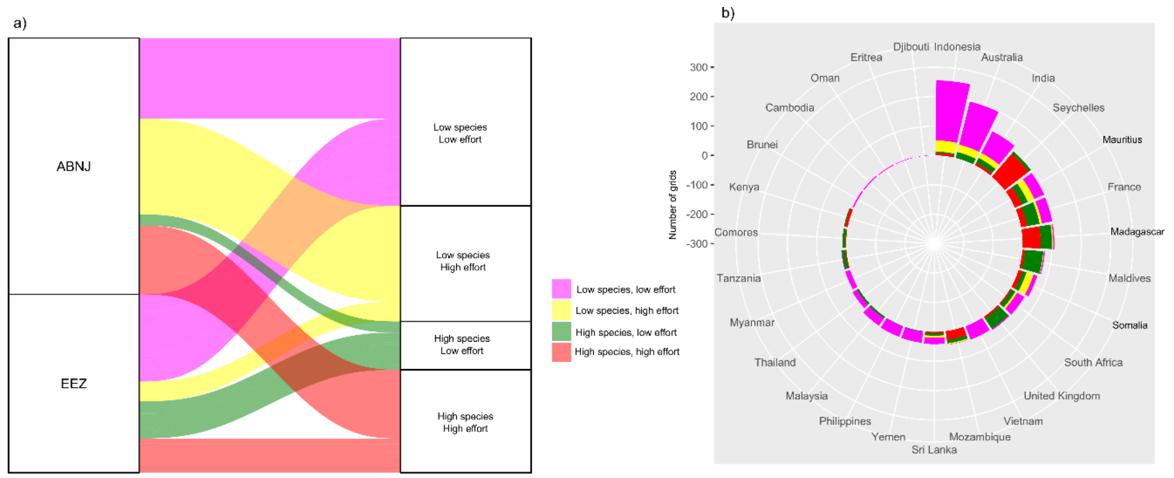

Figure 3.1.7: A, Impacts of fishing effort on the Distribution of billfish species, areas are categorised according to the level of fishing effort (Low, high) and the number of species (Low, High) in the EEZ ABNJ. B. Alluvial plot showing the proportion of EEZ and ABNJ occupied by the different billfish species classes and fishing effort interaction. The species and fishing effort interaction classes are similar to those presented in figure 3.1.6b.

3.4 Sensitivity test

Using two approaches to modelling: pseudo-absences and an alternate method that considers swordfish presence as believable absences, our sensitivity test reveals a minor difference in billfish distribution projections. The overall spatial pattern of projected distribution along the IO is quite similar; however, the exhibited similarity was > than 78% for all species, except for the short bill spearfish, where the similarity between the two projected distributions was 60%. The pseudo-absence method was more conservative and projected a relatively smaller distribution than the swordfish presence – pseudoabsence method (Figure S 3.1.5).

Discussion

We investigated the spatial distribution of six billfish species in the IO and their dependence on the prevailing environmental conditions. To evaluate the likely effects of fishing pressure on billfish species, we tested whether observed fishing effort overlapped with inferred spatial distributions. Overall, our findings show that billfish species in the IO exhibit distinct spatial distributions. Niche partitioning existed among the six species based on physiological tolerances for temperature, MLD and salinity. Furthermore, our study revealed regions where billfish species were strongly associated with the longline fishing effort distribution, suggesting that there may be a need to accelerate measures for billfish management in the EEZs and ABNJs.

Spatial distribution of billfish

The results of our study demonstrate that billfish species in the IO exhibit both niche partitioning and co-occurrence. Based on billfish species' occurrence records in public databases, we identified potential species distributions and associated environmental limits. The northern, western, and eastern IO are vital distribution regions for billfishes. High niche distribution of all species for specific areas, particularly in the northern and western IO areas, may be influenced by high productivity (Prasanna Kumar et al., 2009; Wiggert et al., 2005). Our findings are consistent with reports of shifts in black marlin distribution primarily driven by high nutrients and warm SST from coastal upwelling in the Pacific Ocean (Farchadi et al., 2018). High billfish diversity in Africa's northern and east coast suggests that these areas are conducive environments for billfishes. However, this finding should be subjected to further investigation given fewer occurrence records for this area in the database (Lévy et al., 2007; McCreary et al., 2009).

Relative importance of environmental covariates

The most important variables in billfish habitat suitability were temperature, MLD and salinity. The IO exhibits a wide range of environmental factors (Fig 4). For example, the northern IO, off the eastern coast of Africa, and western Australia experiences high temperatures with minimal seasonal variation because of little exchange with external water masses (Wafar et al., 2011). In contrast, the southern IO region experiences lower temperatures with strong seasonal variability due to the water exchange between the IO and the Atlantic Ocean at high latitudes and between the IO and the Pacific Ocean at low latitudes (Longhurst, 2010; Reygondeau et al., 2012; Wafar et al., 2011). Ocean conditions in northern IO are also influenced to a large extent by the monsoon cycle. The interchange between the northeast and southwest monsoon creates a distinct zone with a subtropical gyre that leads to upwelling and higher productivity and subsequently wider distribution of the billfish species in this region (Schott and McCreary Jr, 2001b; Shankar et al., 2002).

The extent of the predicted spatial distributions varied among the six billfish species. These variations may be mainly due to differences in environmental ranges in the predicted distribution. For example, the swordfish had a broader geographic range, while the marlins had a much narrower geographic range. Our results reinforce previous findings that swordfish have wider temperature ranges than the other billfish species (Boyce, 2004; Boyce et al., 2008). Wider geographic ranges confer species' resilience to climate change, while species with narrow ranges are more exposed to climate impacts (Ofori et al., 2017).

Potential unintended effects on billfish from the longline fishing effort.

The high niche overlap of the six billfish species in the northern IO is also consistent with the catch and effort distribution of other pelagic species such as tuna, which are commonly caught together with billfish in various industrial fishing gears, especially longline and offshore gillnet fisheries (IOTC, 2020a; Lee et al., 2005; Mohri and Nishida, 1999). Longline fishing in the IO mainly targets high-value tunas and swordfish (IOTC, 2020b). Since billfish are highly susceptible to becoming bycatch in tuna and other fisheries, an increased effort targeting tuna can significantly impact billfish populations. Our findings demonstrate that overfished species (black marlin, blue marlin, and striped marlins) highly overlap with zones of high fishing effort. The high overlap between the species' spatial distributions and fishing effort corresponds to recent stock assessments (Andrade, 2016; IOTC, 2020a; Yokoi and Nishida, 2016). The high spatial overlap between longline fishing effort and spatial distribution of black marlin, blue marlin and striped marlin might explain the overfished status of the three species.

Management implications

Our research has key implications for the conservation and management of billfish species in the IO. First, identifying the billfish spatial distributions and niche overlap can inform billfish management as single species, multispecies, or an ecosystem-based approach to management (Möllmann et al., 2014; Vinther et al., 2004). Currently, billfish in the IOTC's area of competence are managed chiefly as single stocks. Our findings on species' distinct niche preferences and niche overlap demonstrate that the IO provides important habitats for these species, underscoring the need for ecosystem-based management both within EEZs and high seas. Second, identifying heavily fished areas relative to the billfish spatial distribution highlights the necessity to identify important marine areas where area-based management approaches could be applied. Third, understanding the critical environmental variables which correlate with billfish distribution may be important in determining how climate change may impact species occurrence in the future.

In a multispecies fishery, it is important to understand the level of species interaction to determine the levels of control to put in place, such as total allowable catch (TAC), especially when vulnerable and threatened species exist together with key targeted species (Pascoe, 2000). Given that three of the billfish species are considered overfished, specific strategies can be formulated accordingly to reduce the detrimental impact of fisheries. Our study demonstrates a significant niche overlap between the overfished species (black marlin, blue marlin, and striped marlin) and those not classified as overfished species. Therefore, unregulated exploitation in these areas of overlap may further increase species' susceptibility to overexploitation, especially for co-caught species such as blue marlin and striped marlin. The interaction between billfish species and other commonly targeted fish species such as tuna and swordfish represents both a risk and reward for implementing management measures (Crespo et al., 2018b; Fonteneau and Richard, 2003). The co-exploitation of these species raises management concerns and indicates that the protection of depleted stocks can only be achieved by reducing the overall catches of billfish and related target species in the IO. However, such an approach would be challenging due to the opportunity cost of other commercially viable species, such as swordfish and some tuna species, which are still being exploited at sustainable rates in the region (IOTC, 2020a; Pascoe, 2000; Pascoe et al., 2015). Even though this choke species scenario does not represent optimal management, the requirement for fisheries to be managed according to the principles of ecologically sustainable development and the precautionary principle should prevent the continual overexploitation of depleted stocks over the short-term economic gains (Baudron and Fernandes, 2015).

Currently, the stock status of shortbill spearfish in the IO is unknown. Our results indicate that the shortbill spearfish has the smallest spatial distribution, which overlaps strongly with areas of high fishing effort, especially in the south-western IO. For the first time, we show that the predicted distribution of shortbill spearfish overlaps highly with fisheries and may require a targeted management response, including intensified data collection to address the substantial data gaps. Precautionary fisheries management approaches could be applied mainly in the EEZs of the Western IO, where its niche is centred (Garcia, 1994; González-Laxe, 2005; Karim et al., 2020). The high seas occupy approximately half of the study area and comprise the spatial distributions of most of the billfish species. Yet fishing effort has increased tremendously in the high seas (Swartz et al., 2010). The limitations associated with monitoring, control and surveillance of the EEZs and high seas in the IO predisposes the billfish species to overfishing (Agnew et al., 2009; Riskas et al., 2018). The need to provide additional management measures to safeguard species caught within the high seas has been of interest to the international community (Crespo et al., 2019; Marsac et al., 2020). Our paper further emphasises this need by identifying that high billfish species richness overlaps with fishing pressure. These areas may provide focal points for fisheries management approaches within the high seas. Also identified are areas with high species diversity and low fishing effort, which could be a priority for establishing spatial conservation measures. Additionally, we point out specific nations that may be more significant for billfish management.

Climate-driven changes, such as changes in water temperatures, have been shown to have likely impacts on billfish species (Dell'Apa et al., 2018). Our study indicates that temperature and MLD significantly influence the occurrence of billfish species in the IO. This shows that future climate change uncertainties continue to pose a threat to billfish fisheries and the coastal populations that rely on them for survival (Dell'Apa et al., 2018; Grose et al., 2020). Hence an adaptive management framework should be considered when developing billfish management actions in the region (Chang et al., 2019; Walters, 1986). Adaptive management considers uncertainties, such as potential changes in water temperature and capacities of species to adapt to these changes, which is a more practical approach to addressing climate-driven changes in fisheries (Daw et al., 2009; Ogier et al., 2016).

Limitations

Models may be limited by the data used to generate them. This study was carried out in a data scarcity context and within the data availability limitations, particularly in areas where billfish data and longline fishing effort are under-reported or/and lacking. Our findings are based primarily on longline fishing effort, given the data scarcity. In particular, the determination of the spatial congruence between the identified spatial distributions and fishing effort should be interpreted with caution, given that catch data (albeit from other sources) was used in generating the spatial distribution maps. Moreover, data from offshore gillnet fisheries, conventional and satellite tagging from recreational fishers and artisanal landings in future studies may provide improved predictions of billfish partitioning in the other areas within the IO. Nevertheless, our findings provide a starting point to understanding the influence of various fisheries sectors and environmental factors on billfish distribution, emphasising the urgent need for comprehensive data.

Conclusion

Our findings depict niche partitioning and overlap of the six billfish species in the IO, greatly influenced by temperatures, MLD and salinity. Our analysis suggests that more effort is required to record billfish occurrences and fishing effort adequately. Our results highlight species' hotspots' that could provide a focus for billfish management, including ecosystem-based, adaptive, and precautionary approaches to managing these threatened species across maritime zones. These findings can inform countries' actions in the IO towards sustainable exploitation and management of billfish, which is necessary for securing socio-economic and cultural security for local communities dependent on fisheries (Kadagi et al., 2021a; Okafor-Yarwood et al., 2020).

Supplementary material.

Table S3.1.1: Number of occurrence points used for the Species Distribution Modelling

Species	OBIS	IOTC	Total
Black marlin	321	1998	2319
Sailfish	665	1861	2526
Striped marlin	425	1997	2422
Blue marlin	118	2020	2138
Short bill spearfish	89	177	266
Swordfish	1179	1543	2722

Table S3.1.2: Description of data sources (Spatial resolution is 0.083 degrees by 0.083 degrees)

Variable	Dataset Name	Sources
Temperature, mixed layer depth (MLD), sea surface height (SSH) and salinity	(GLOBAL_REANALYSIS_PHY_001_030)	Global Ocean Physical Reanalysis. http://marine.copernicus.eu/services-portfolio/access-to-products/
chlorophyll	(GLOBAL_REANALYSIS_BIO_001_029)	Global Ocean Biogeochemistry hindcast. http://marine.copernicus.eu/services-portfolio/access-to-products/

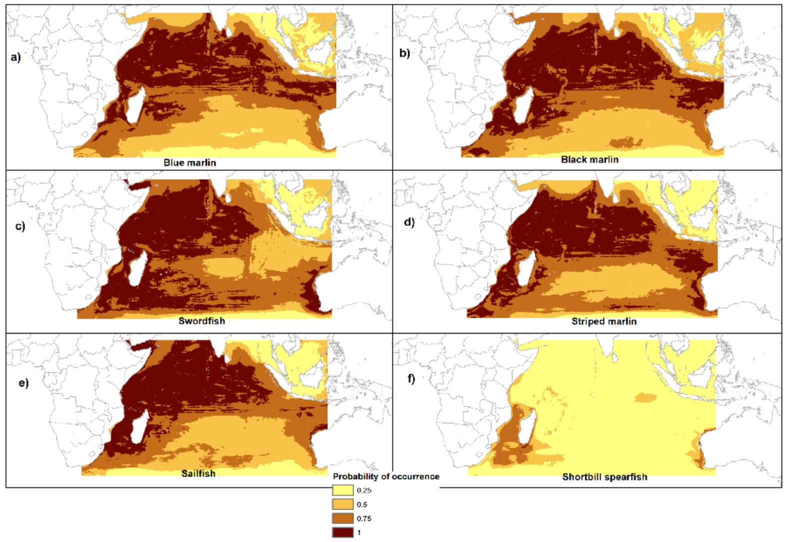

Figure S3.1.3: All species ' probability maps (probability of occurrence) derived with form the ensemble modelling.

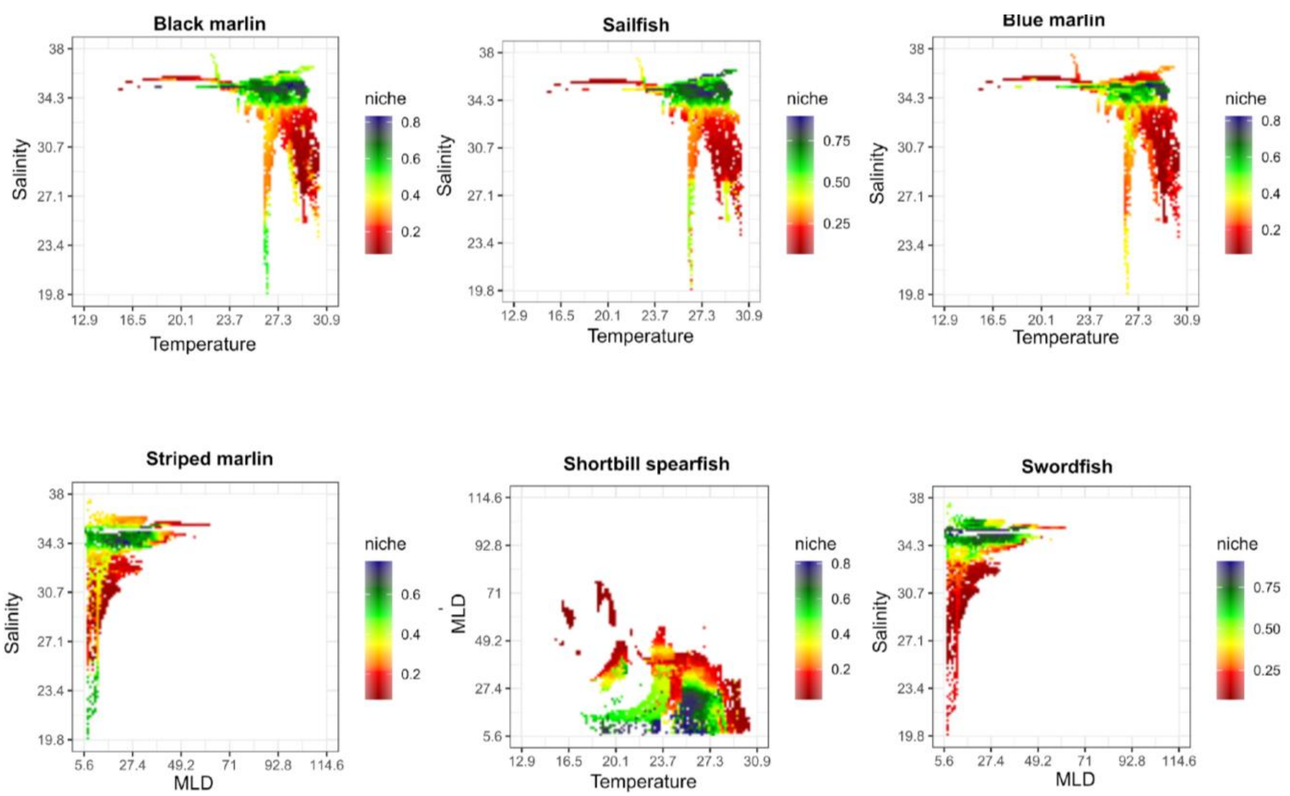

Figure S3.1.4: Niche plotted against the two most important predictor variables.

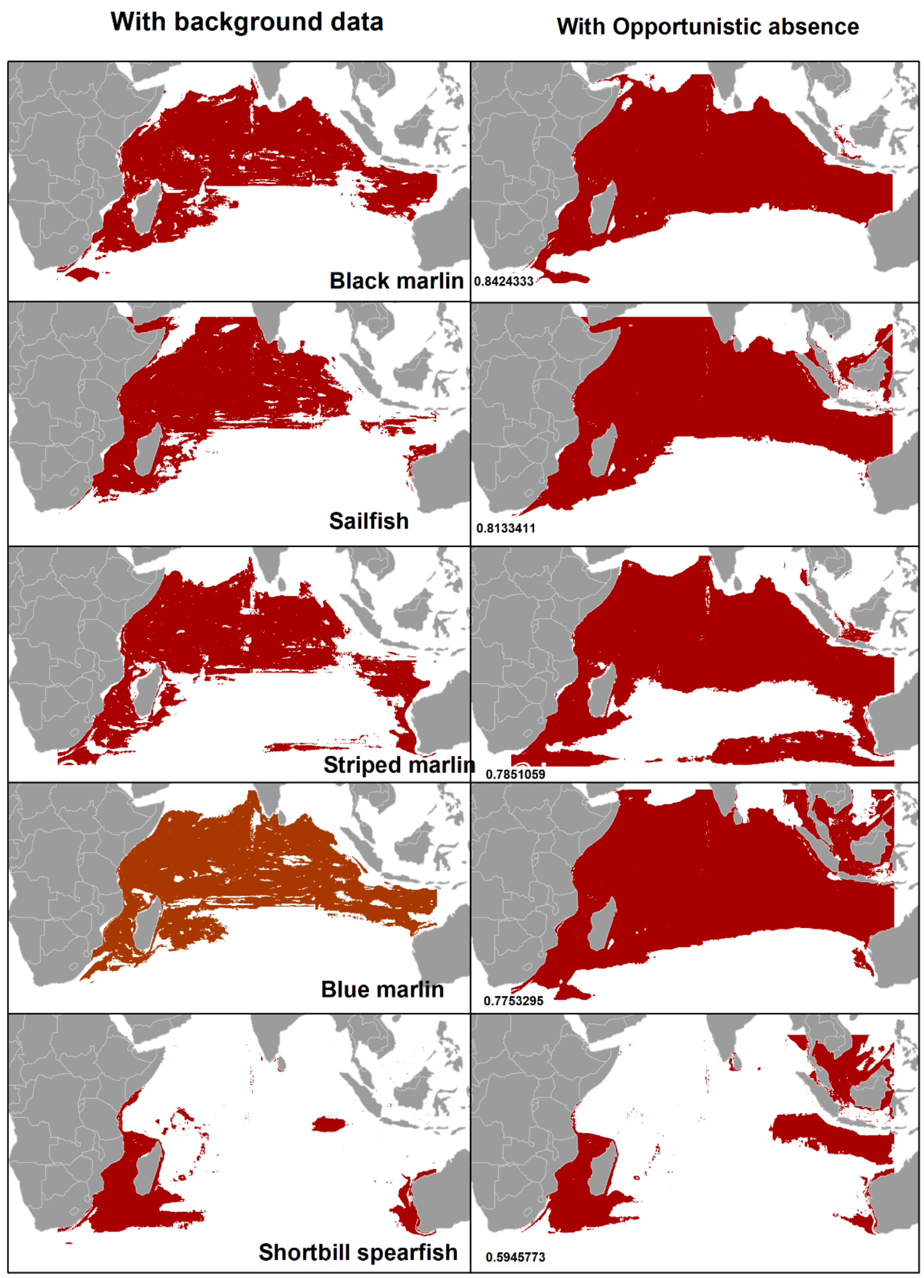

Figure S3.1.5: Results of sensitivity testing using pseudo-absence data and swordfish presence as opportunistic absence data. The two approaches showed similar spatial patterns of projected niches; the niche overlap value is indicated for each species.

Table S3.1.6: Evaluation metric, true skill statistic (TSS) for all species distribution models (mean value of 10 model runs)

Species	GLM	GAM	GBM	RF
Black marlin	0.512	0.625	0.623	0.704
Sailfish	0.683	0.682	0.754	0.732
Striped marlin	0.373	0.570	0.634	0.691
Blue marlin	0.649	0.386	0.812	0.857
Shortbill spearfish	0.655	0.607	0.607	0.607
Swordfish	0.555	0.561	0.641	0.668

3.2 Case study 2. Policy gaps in the East African Blue economy: Perspectives of small-scale fishers on port development in Kenya and Tanzania.

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Key Words: Blue economy, blue justice, small-scale fisheries, Port development, Participatory mapping.

Abstract

Recently, the rights of small-scale fishers have increasingly been acknowledged in ocean governance because coastal development and various maritime activities have reduced traditional fishing grounds. More specifically, small-scale fisheries (SSF) are increasingly being threatened by ocean grabbing, pollution, and lack of inclusiveness in decision-making processes. Although there are guidelines to resolve and reduce conflict, formal avenues to include fisher concerns, particularly in the context of ocean development and governance, remain a difficult task. Moreover, there is insufficient information on how fishers are impacted by coastal and marine development and how their concerns are included in decision-making process. Hence, this study contributes to the SSF discourse by understanding and describing the characteristics and concerns of small-scale fishers from two coastal towns in East Africa with different levels of port development. Using data from perception surveys, focus group discussions and participatory mapping, we discuss how fishers were involved in the decision-making processes to develop ports in Lamu, Kenya and Bagamoyo, Tanzania. We found that fishers rely on nearshore ecosystems such as mangroves and coral reefs, because of their accessibility since most fishers only use low-powered boats for fishing. Moreover, we found that the fishers' livelihoods were severely affected by port development, and that they were excluded from decision-making process concerning the ports construction and fishers' compensations. While some fishers believe that new ports in the region can increase their livelihoods by creating new markets and jobs, this unlikely to happen since most fishers are not qualified to work in formal port-related jobs. We propose three steps that will allow fishermen to participate in port development decision-making processes and contribute to the development of a sustainable SSF. These include improving the engagement with fishers to allow meaningful participation in decision-making, developing a blue economy policy focused on SSF, and implementing maritime spatial planning.

Introduction

Small-scale fisheries (SSF) contributes to food security worldwide and provides jobs to millions of people, especially in developing countries (Bevitt et al., 2021). Moreover, SSF is an economically important coastal livelihood activity in East Africa, because it has been estimated to employ approximately 50,000 fishers (GoK, 2016; Sector, 2016). SSF in East Africa is characterised by artisanal fishers that use non-motorised boats like canoes and small sailboats, which are easy to use and manoeuvre in nearshore areas, to fish for subsistence and earn some income (McClanahan and Mangi, 2004; UNEP-Nairobi Convention and WIOMSA, 2015; Van der Elst et al., 2005). Despite the importance of SSF's to the socioeconomic development of coastal communities in East Africa, the interests of fishers is largely ignored by government development agendas. Moreover, small-scale fishers are increasingly experiencing reduced access to fishing areas (Thoya and Daw, 2019), low catches due to overfishing and degraded coastal and marine ecosystems (Jackson et al., 2001), a weak market for their seafood (Purcell et al., 2017; Wamukota, 2009), conflicts with large-scale fishers (Munga et al., 2014), and problems with recent blue economy development such as oil and gas exploration and port expansion (Rodden, 2014).

Many government and civil society organisations worldwide are increasingly advocating for more meaningful engagement of small-scale fishers in decision-making processes to give them space to raise their socio-economic rights (Bennett et al., 2021). As such, participatory processes have been promoted to reduce inequity and injustice in society while fostering a fair distribution of costs and benefits of coastal and marine resource development (Agyeman, 2005). The need to safeguard small-scale fisheries and include fishers in stakeholder engagement processes is recognised worldwide, because fishers make up the biggest group of marine resource users and significantly contribute to global food security (FAO, 2020). The Food and Agricultural Organisation's "Voluntary Guidelines for Securing Small-Scale Sustainable Fisheries in the Context of Food Security and Poverty Eradication" (hereafter FAO SSF Guidelines) ratified in 2014, emphasise the importance of securing the tenurial rights of small-scale fishers, which include providing them equal access to fishery resources and fishing grounds (Kurien, 2015). However, the implementation of these guidelines has been resisted in many regions and are yet to make the desired impact on local communities (Jentoft et al., 2017).

Another important initiative advocating for SSF rights is the "blue justice" movement, led by the Global Partnership for Small-Scale Fisheries Research (TBTI, 2021). Blue justice is a critical approach to promoting sustainable ocean development by investigating how ocean-based development affects coastal communities and SSF. It arose from the recent interest of countries to expand the maritime sectors, commonly referred to as the blue economy (BE), which threatens the sustainability of the SSF (Bennett et al., 2019). Blue justice advocates for the historical rights of small-scale fishers and coastal communities, and urges governments to reduce pressures that are likely to jeopardise the rights and well-being of fishers (Arbo et al., 2018; Bennett, 2019).

As with other countries, East Africa have adopted the blue economy concept with the United Nation's Nairobi Convention, COP 8 decision supporting the strengthening of ocean governance strategies to enhance blue economy activities in the region. The government of Kenya, for example, values the importance of the blue economy and its potential role to improve the Kenya's economy overall. Hence, the Kenyan government has mandated the expansion of mariculture, shipping and transportation, tourism, and oil exploration, which have been identified by the government as key to achieving the ambitious country's economic developing plan 'vision 2030'. Moreover, the government prioritised blue economy activities as part of the state department for fisheries, aquaculture and the blue economy (GoK, 2007; Sharon, 2020). Similarly, Tanzania has put the blue economy at the centre of its economic growth and has created a comprehensive roadmap for its blue economy development (Hafidh et al., 2021). Although the blue economy has enormous developmental potential for East African countries, the current trend toward ocean-based economic development raises concerns, because it can conflict with the achievement of blue justice objectives (Okafor-Yarwood et al., 2020).

The effects of the promotion of the development of the East African blue economy on stakeholders, particularly those who may be adversely affected by large-scale growth linked with it, are yet to be determined. Moreover, there is currently insufficient information on how small-scale fishers are affected by port developments in East Africa and how their concerns are considered in decision-making. To help address this gap, this study aims to understand and present the perceptions of small-scale fishers in relation to port development in Kenya and Tanzania using blue justice as a broad analytical framework. We selected two coastal towns each in Kenya and Tanzania, because of their similar histories and contexts, levels of resource use, and governance arrangements. However, both countries have slightly different economies, with Kenya classified as a lower middle-income country and Tanzania as the least developed country per the Organization for Economic Co-operation and Development (OECD, 2021).

2.0 Materials and Methods

2.1 Study Area

While both Kenya and Tanzania have major ports located in the cities of Mombasa and Dar-es-salaam, respectively, the governments of both countries have started to enhance their maritime transportation infrastructure to support economic growth and expansion of the ocean economy in East Africa (Kanai and Schindler, 2019; Rasowo et al., 2020) (Figure Figure 3.2.1.). Currently, the ports are being developed north of Mombasa in Lamu county in Kenya, and in south of Dar es Salaam in Bagamoyo district in Tanzania. Both ports have financial support from foreign investors, particularly the Chinese government (Hönke and Cuesta-Fernandez, 2018; Were, 2019).

The Lamu port is located on Lamu Island near the Somali border in the north of Kenya (Figure 1). The port is part of the larger Lamu Port, South Sudan, Ethiopia Transport Corridor (LAPSSET). The LAPSSET corridor program is Eastern Africa’s largest and most ambitious large-scale infrastructure project linking Kenya, Ethiopia, and South Sudan to improve access and transport, and consequently economic development. When completed, the project will have highways, railway lines, and oil pipelines constructed traversing the three countries (LAPSSET, 2021). The port is still under construction and will have 32 berths upon completion (LAPSSET, 2021).

The Bagamoyo port is located 60km from Dar-es-salaam in Tanzania. It falls within the area where the government plans to create a Special Economic Zone (SEZ) to decongest the Dar-es-salaam region. The port will serve as a transportation hub for processed commodities that local businesses produce (Kanai and Schindler, 2019).

Data collection was conducted in September and October 2019, in both Lamu and Bagamoyo. The field data collection included participatory mapping exercises with invited fishers, and community perception surveys. During field work in Lamu, the construction of the first three berths of the port was about 80% complete. Currently, there are four berths that are operational. In Bagamoyo, initial plans for the development of the port had already been undertaken, including land compensation.

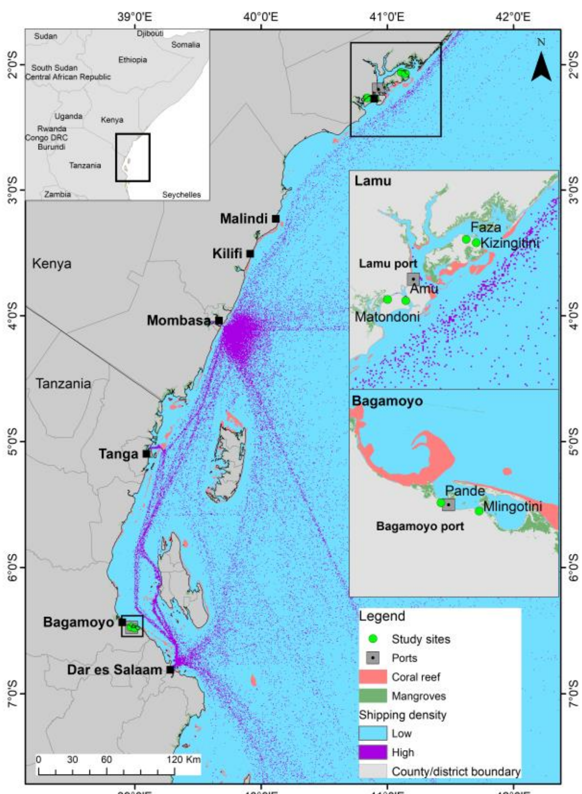

Figure 3.2.1. The county of Lamu is located north of Mombasa, which is a major port city in Kenya. The Bagamoyo district is located north of Dar es Salaam, which is the capital and a major port city of Tanzania.

2.2 Participatory mapping

We used the participatory mapping approach described by Daw et al. (2011) to locate and characterise high-value fishing grounds for small-scale fishers. Generally, participatory mapping elicits fishers' spatial knowledge of their fishing areas through group discussion and visual aids such as maps (Kafas et al., 2017; O. Nyumba et al., 2018; Silvano and Hallwass, 2020). The computer-based maps, which were produced using the Google Earth Engine©, depict locations in nearshore areas with easily recognised habitats such as coral reefs and mangroves. We conducted a total of four participatory mapping sessions from September 2019 to October 2019, two in Lamu and two in Bagamoyo. The sessions were held in Faza and Amu location in Lamu, and Mlingoni and Pande in Bagamoyo. Each session took about 2 hours to complete for each study area. The lead author (PT) led and ran the participatory mapping sessions, which included 25 fishers in each location (n = 50 fishers in Lamu, n = 50 fishers in Bagamoyo). The participants that were invited represented artisanal fishers that used the four most commonly used fishing gears (i.e., spear, net, trap and line). According to (Krueger, and Casey, 2000), a group of six to eight people is adequate for a focus group discussion, but a larger group of fishers attended the discussions due to the encouragement of fishing group leaders. Working with fishing group leaders, they identified and recommended fishers that have had a long history of fishing (i.e., at least 10 years). More experienced fishers were invited, because they are known to have greater precision in identifying a fishing grounds exact location. The sessions were all conducted using Swahili, the official language in both study areas and countries, to ensure the effectiveness of communication and proper documentation of the data.

The first step in the participatory mapping process asked fishers to identify key land-based and nearshore geographic and bathymetric features such as houses, coral reefs, and islands on Google Earth©. Second, using the markers and features as a basis, fishers were asked to delineate the extent of the fishing grounds. As the participants identify the fishing grounds, discussions also involved fishers' local ecological knowledge and fisheries, particularly the key fishing grounds and spawning areas, biophysical qualities such as depth and habitat types, and their preferred fishing gears. By characterising the SSF into sub-groups, we can understand which fishing grounds areas are essential and accessible to fishers and how port developments can affect their livelihoods. The fishing grounds identified on the Google Maps were saved in Google Earth Pro and analysed in ArcMap (ESRI).

2.3 Perception surveys

We conducted semi-structured in-person perception surveys with a total of 189 fishers from October to September 2019. In Lamu, we surveyed 97 fishers from beach management units (BMUs) surrounding the port, which included Amu, Matondoni, Shella, Kizingiti, Pate, and Faza, where the impacts of the port development will most likely be felt (Figure 3.2.1). For Bagamoyo, we interviewed 92 fishers from Pande and Mlingotini, the closest SSF landing area to the port area. The BMUs consist of individuals who traditionally depend on fisheries activities for their livelihoods (e.g. fishers, fish traders, boat owners and fish processors) (Oluoch and Obura, 2008). Moreover, BMUs are also informal governance units that are typically responsible of coastal management and named after villages, which are recognised as part of the co-management system of ocean governance in Kenya and Tanzania.

The in-person perception surveys was done, because it was a good approach for extracting meaningful information about fisheries to help understand problems experienced by fishers, which include reduced access to marine space (Daw et al., 2011; Silvano and Hallwass, 2020). The number of fishers that participated in the survey represents 20% of the total fishing population in the study sites, which was regarded as an adequate representation of the collective experiences in the BMUs (Dzoga et al., 2018). Only fishers who agreed to participate in the survey were chosen, because conversations about fishers' fishing grounds are considered private (Daw et al., 2011). The survey participants included all fishers that attended the participatory mapping sessions, and other fishers that were chosen at random by the BMU leaders. The lead author (PT) and two research assistants conducted all the surveys in all of the BMUs using the same questionnaire. Each survey lasted about an hour and was conducted in Swahili, the official language of all the study locations.

The survey was structured in two parts. The first part was designed to obtain demographic data about the fishers (e.g., age and number of years fishing) and information about fishing practices (e.g., number of days fishing per week, fishing gears and boats used, and targeted fish families. Fishers were also asked to identify their preferred fishing grounds from the list of locations generated from the participatory mapping exercise. The second part aimed to understand fishers' perspectives on port development and their perception on the impacts of port development on SSF. Some questions included: i) If the fishers used to fish at the port area; ii) if the fishers were engaged in decision-making; and, iii) how the port has affected their livelihoods, the environment, and ecosystems. A follow-up inquiry was asked on the specific impacts each fisher had experienced, whenever needed. The responses were recorded in English and then transferred to an excel spreadsheet for further analysis.

2.4 Data analysis and synthesis

The results of the participatory mapping and perception surveys were analysed by: i) defining fisheries attributes and the importance of key habitats to the SSF in each of the study areas; ii) describing the impacts of port development and its implications on SSF; and, iii) evaluating and identifying blue economy policy gaps in each of the countries to mitigate the impact of port development on SSF.

To evaluate the importance of the different ecosystems to SSF, we estimated the fishing intensity in the three primary habitats which are coral reefs, mangroves, and pelagic habitats. The fishing intensity was calculated by getting the sum frequency of fishers that identified their preferred fishing grounds during the surveys. We then identified the most important habitats for the fishers by measuring the distance between the identified fishing grounds to the nearest coral reefs and mangroves. Using the coral reef and mangroves maps shapefiles from the UN Environment Programme World Conservation Monitoring Centre (UNEP-WCMC)(Giri et al., 2011; UNEP-WCMC and WRI, 2021) we calculated the distance of the fishing locations to the habitats different habitats. A fishing location within a 1-km radius of coral reefs was categorised as a coral reef fishing ground, whereas those within a 1-km radius of mangroves were categorised as in the mangrove fishing ground. Fishing grounds within a 1-km radius of both mangroves and coral reefs were categorised as coral-mangrove fishing grounds. Because coral reefs and mangroves occupy the shallow area in the study area, the fishing locations outside the 1-km radius of coral reefs and mangroves were deemed to be in offshore areas and were categorised as pelagic fishing grounds.

The fisher characteristics and perception of port development impacts were analysed using descriptive statistics, including central tendencies such as means, medians, and percentages. The fisher characteristics for both study areas were presented and analysed to allow for quantitative comparisons. Additionally, the targeted fish families described in the survey were also aggregated according to ocean zones, which was also used to validate the described preferred fishing grounds.

For the blue economy policy gaps, we used Bennett et al. (2021) review as a broad analytical framework. Bennett et al. (2021) posited that there are 10 main domains that may hinder the achievement of a sustainable blue economy and blue justice. These include: i) dispossession, displacement and ocean grabbing; ii) environmental justice concerns from pollution and waste; iii) environmental degradation and reduction of availability of ecosystem services; iv) livelihood impacts for SSF; v) lost access to marine resources needed for food security and wellbeing; vi) inequitable distribution of economic benefits, Vii) social and cultural impacts; viii) marginalization of women; ix) human and Indigenous rights abuses; and, x) exclusion from governance. Since blue justice research is still in its infancy and was not factored in our original research approach, we applied an inductive coding procedure to our original questions to facilitate the incorporation of the novel knowledge of blue justice domains outlined by Bennett et al. (2021). Since fishers were asked how they were affected (i.e., positive, negative, or neutral) by port development in their different life aspects (e.g., livelihood, fish market, access to the fishing area). We calculated the proportion of fishers who replied in each category and referred the results to the coded blue justice domains. throughout the discussion.

3.0 Results

3.1 Fishers' characteristics.

The characteristics of fishers and fishing activities in both study areas are very similar. All the fishers surveyed in Lamu and Bagamoyo were men and had an average age of 41 and 44 years, respectively (Figure 3.2.2a). Most of the fishers interviewed had substantial fishing experience, with the average number of years fishing of 24 years for fishers in Lamu and 23 years for fishers in Bagamoyo (Figure 3.2.2b). Most fishers from both study areas used wooden boats ranging from 2 to 20 meters in length and fished for six days a week on average (Figure 3.2.2c). The majority of fishers surveyed in Lamu and Bagamoyo had a daily income less than $20 (Figure 3.2.2d) and spent up to 6 years on average in school (Figure 3.2.2e). There were differences in propulsion modes for fishing boats with most of the fishers in Lamu used fishing boats with engines (73%) and sailboats (23%). In Bagamoyo, the majority of fishers reported the use of paddle boats (59%), sailboats (25%) and motorised boats (16%) (Figure 3.2.3). In terms of preferred fishing gears, fishers in Lamu mostly used seine nets (31%), handline (25%), gill nets (21 %), and spear (25%). Whereas, in Bagamoyo, handlines (47%) and gillnets (45%) were the most commonly used fishing gears (Figure 3.2.3).

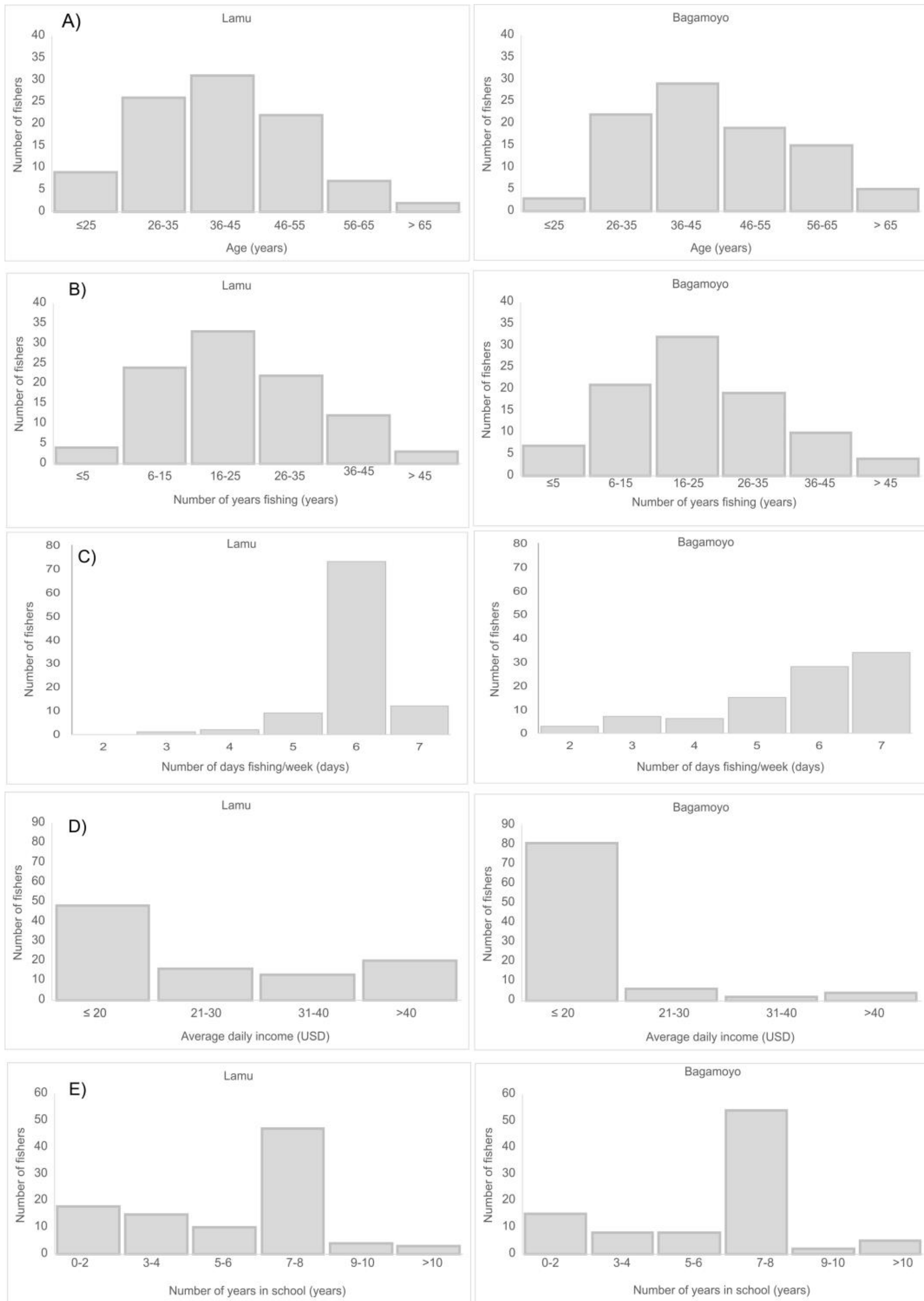

Figure 3.2.2: Summary of different fisher characteristics in Lamu (left panel) and Bagamoyo (right panel). Fishers' characteristics include a) age; b) number of years fishing; c) number of fishing days per week; d) daily income; and e) number of years spent in school.

For the targeted fishes, 75% of the respondents in Lamu targeted demersal fish families that are often found in or near coral reefs. These include Palinuridae (lobsters), Scombridae (tuna), and Lethrinidae (emperors). In Bagamoyo fishers targeted lethrinids, palinurids, and carangids (trevallies or scads) (Figure 3.2.3). Lobsters are considered as high-value species collected by divers using harpoons.

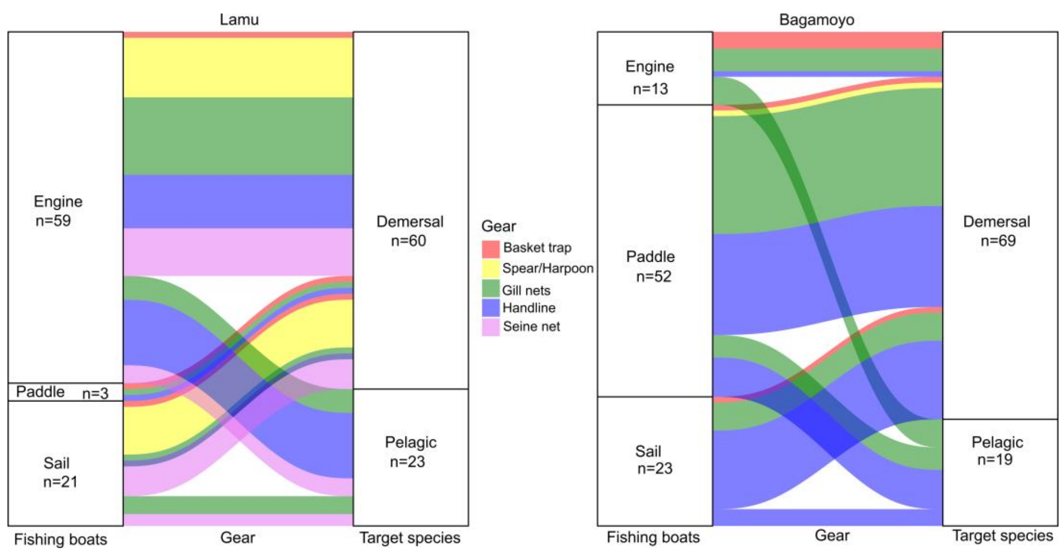

Figure 3.2.3. Diagram describing the diversity of types of fishing boats and gears used, and the targeted species groups by fishers from Lamu (left panel) and Bagamoyo (right panel).

Important fishing grounds

Coral reefs and mangroves were identified as the most preferred fishing habitats for the majority of the respondents in both Lamu and Bagamoyo (Figure 3.2.4). More specifically, 34% of fishers in Lamu identified coral reefs as the most favoured fishing grounds, followed by mangroves with 22% and pelagic waters with 19%. For the respondents in Bagamoyo, 27% fished in coral reef-mangrove areas, 19% in mangrove areas and 16% in coral reefs. Spatially, fishing intensities varied across the different habitats. For fishers in Lamu, fishing grounds with the highest fishing intensities mostly overlapped with coral reefs followed by pelagic waters. Similarly, in Bagamoyo, coral reefs had the highest fishing intensities, followed by mangroves. Most of fishing grounds identified were within 10 kilometres of both ports in Lamu and Bagamoyo (Figure 3.2.5).

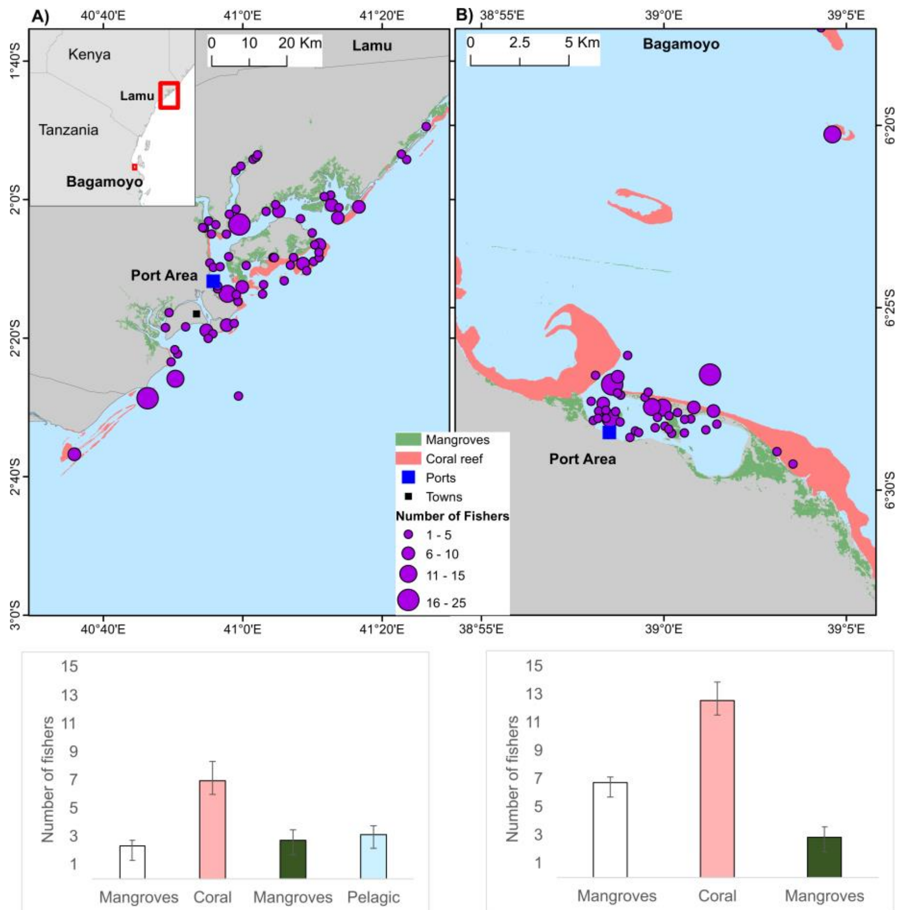

Figure 3.2.4. Distribution of fishing effort and fishing intensities based on the number of times the fishers mentioned a fishing ground in the interviews in a) Lamu and b) Bagamoyo. The bar charts indicate the mean number of fishers in the four habitat categories. Error bars present standard error of the mean.

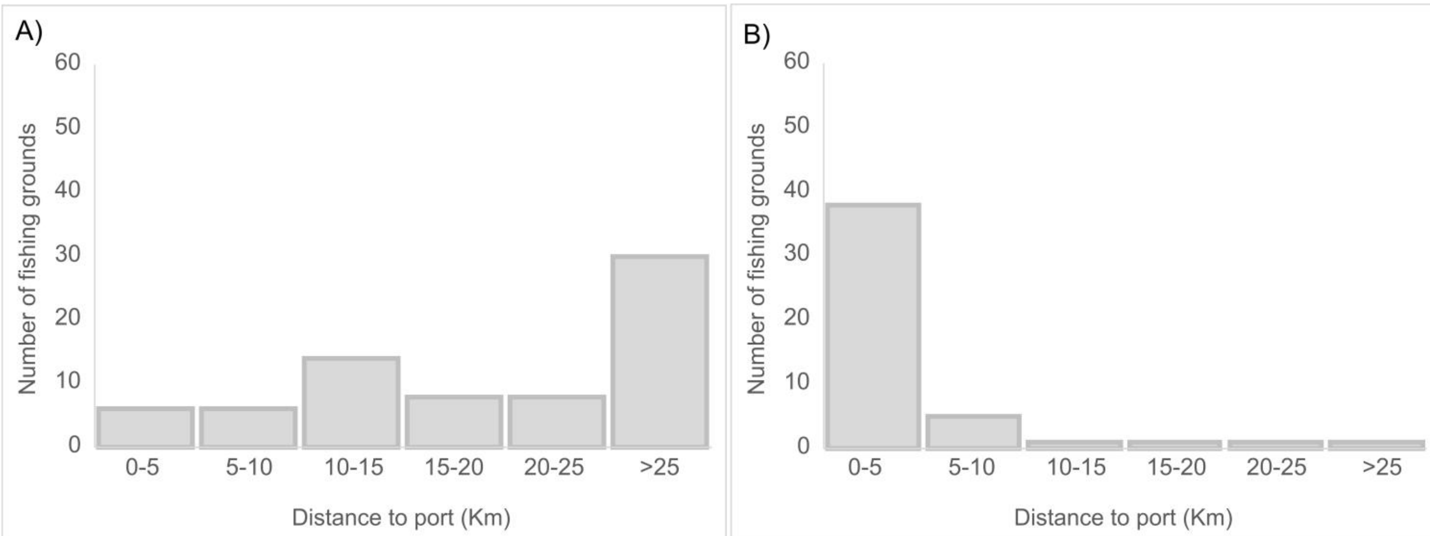

Figure 3.2.5. Distance between the preferred fishing grounds of fishers to the port area in a) Lamu b) Bagamoyo.

3.3 Fishers' perception of port development impacts.

Using six of the blue justice domains described by Benett et al. (2021), we describe the perceptions of the fisher respondents in Lamu and Bagamoyo on port development and implementation. The majority of the fishers surveyed in both study areas believed that the proposed ports would have negative impacts on the environment and their livelihoods (Figure 3.2.6).

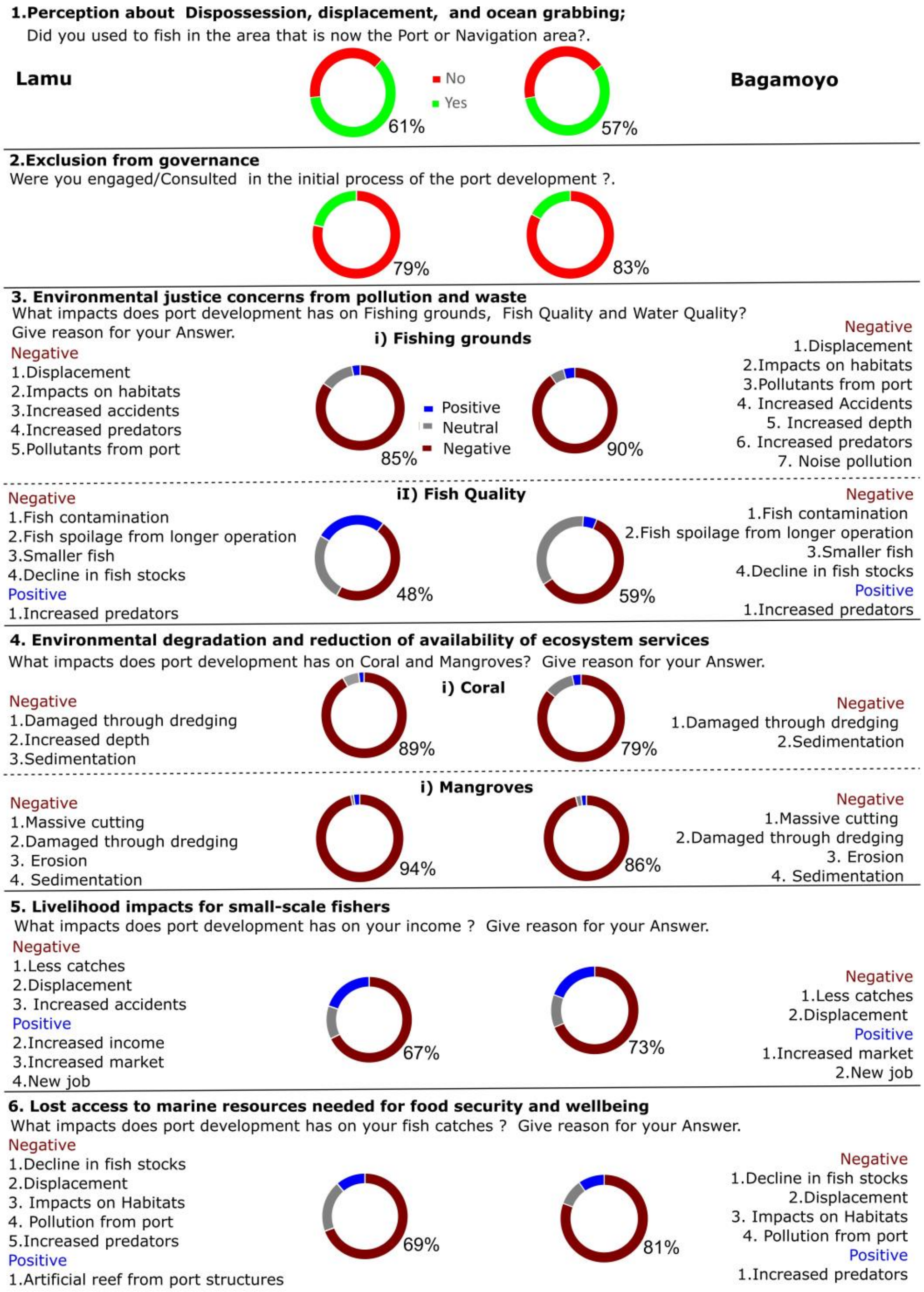

Figure 3.2.6: The perceived impacts of port development on SSF using the six blue justice dimensions (1-6, modified after Bennet et al. 2021).

3.3.1. Dispossession, displacement, and ocean grabbing

Most of fishers surveyed in Lamu and Bagamoyo reported that the proposed port areas were an important fishing ground and that they have been displaced forced to find new fishing grounds (Figure 3.2.6). These findings are consistent with the location of multiple fishing grounds in the port area as shown by maps of fishing grounds and intensities (Figure 3.2.3).

3.3.2. Exclusion from governance

A great majority of fishers surveyed stated they were not involved or at least consulted during the port planning process. However, after probing the BMU leadership and some of the respondents we found that there have been some forms of consultation undertaken, which included interviews, BMU-level consultation meetings and, and public hearings in villages. For those that have been involved in consultation processes, they stated that they were included in a survey, or participated in BMU-level meetings or village-level public hearings. In Lamu, 62% of the fishers were consulted at the BMU-level, 24% personally, and 14% at the village-public hearing. In Bagamoyo, for those who said they were consulted, 31% said they were consulted at the BMU-level, while 69% said they were consulted at the village-public hearing.

3.3.3. Environmental justice concerns from pollution and waste

Port development and implementation are believed to pollute fishing grounds. More specifically 84% and 94% of respondents in Lamu and Bagamoyo, respectively, said that the port would degrade ecosystems and reduce water quality, because of dredging and port operations. Surprisingly, fishers in Lamu feared that the port would attract more predators, such as sharks, which could endanger fishers. Respondents from Lamu had mixed perceptions on the impact of the ports on fish catch; where, only 48% of respondents believed that the ports would have a negative impact, 26% believed there would be no impact; and 26% of respondents believed the port would improve their fish quality. In Bagamoyo, 59% of the respondents believed the port development would reduce fish quality, while 35% believed there would be no impact. Additionally, some fishermen from Bagamoyo believed that increased predators such as sharks would improve fish quality.

3.3.4. Environmental degradation and reduction of availability of ecosystem services

Almost all of the respondents in Bagamoyo and Lamu said that port development would cause the degradation of coral reefs and mangroves. They identified dredging, increased depth, and sedimentation to be the most likely causes of coral reef damage, and mangrove clearing, erosion, and sedimentation to be the potential causes of mangrove forest degradation.

3.3.5. Livelihood impacts for small-scale fishers

The perceptions of fishers on the effects of port expansion on their livelihoods were mixed. In Lamu, most of the respondents thought port development would negatively impact their livelihoods. Reduced catches, displaced fishing grounds, environmental damage, and more accidents resulting in the loss of fishing gear were some of the negative consequences of port development and implementation. Those that claimed the positive effects believed that the port could increase income, expand market bases, and introduce new jobs. In Bagamoyo, most of the fishers said port development would harm their livelihoods. Fewer catches and displacement were suggested as potential negative implications, while new jobs and increased jobs were suggested as beneficial impacts of the port on fishers' livelihoods.

3.3.6. Lost access to marine resources needed for food security and wellbeing

In Lamu, most of the fishers believe their catches will decrease. The drop in fish catch was believed to be due to dwindling fish stocks, habitat changes and displacement, and increased predators. Some fishers thought the port structures acted as artificial reefs and would influence the increase in catches. In Bagamoyo, most fishers thought their catches would also decrease due to the same reasons reported by the fishers from Lamu fishers. However, these respondents believed that increased predators is a sign of good impact on catches compared to the responses of Lamu fishers (Figure 3.2.6).

4.0 Discussion

This study presents the perceptions of small-scale fishers toward port infrastructure development and its potential consequences for SSF in Lamu and Bagamoyo. Many of the fishers that included in the group discussions and surveys were concerned about the potential negative effects of port development. The power imbalance shown by the fishers' lack of meaningful engagement in decision-making processes reveals policy inadequacies that may assure equitable treatment of small-scale fishers as the blue economy expands in the study areas and eventually the entire countries of Kenya and Tanzania. Given the growing importance of coastal and maritime activities in East Africa, this is one of the first studies to describe the possible social and environmental injustices that small-scale fishers may face due to ocean-based developments in the region.

Since the majority of fishers from Lamu and Bagamaoyo use low-capital fishing boats and gears, they are often limited and unable to access offshore fishing grounds (Thoya and Daw, 2019), which makes them more reliant on nearshore and coastal ecosystems like coral reefs and mangroves (Carrasquilla-Henao and Juanes, 2017; Honda et al., 2013). Moreover, the majority of the targeted fish and invertebrate families, which include high-value species such as lobster and crab, depend on nearshore habitats. These high-value species are commonly targeted by fishers because they can earn higher income from them. Hence, it is important to manage activities that can damage nearshore habitats so that nearshore fisheries resources, livelihoods and food sources will not be affected (Fondo and Martens, 1998).

Another important finding of this study was that most fishers believed port development will expel them out of their fishing grounds and damage the fish habitats, which threatens their livelihoods and food security. These perceptions were also supported by participatory mapping results that revealed that most of the fishing grounds highlighted by the fishers are located in areas that are likely to be impacted by the ports, either through pollution, navigation, or habitat conversion to make room for the port area. The impacts are already visible in Lamu, where fishers experienced decreased catches, and some have been forced to quit the fishery. Fishers that use diving methods and low-power fishing boats are the most vulnerable, because their fishing activities are limited to the areas closer to the ports (Thoya and Daw, 2019). While fishers with high-powered fishing boats can adapt by fishing further offshore, this could still increase the cost of fishing due to additional fuel costs compared to fishing in nearshore areas. Because of the high cost of fishing, the catch per unit effort could decrease and the profit margin could shrink (Bastardie et al., 2013).

Better markets often appear to be a reasonable outcome of port development. Hence, some fishers thought the port development would benefit them by boosting their income and livelihood due to potential increased access to new markets and job opportunities. Moreover, Lamu and Bagamoyo are remote from the major cities and towns in Kenya and Tanzania. Fishers from these districts often have low incomes, because their fish catch usually go through intermediaries that pay low prices instead of getting sold in the cities directly. The growing population in the area will almost certainly result in a larger market and higher pricing (Kimani et al., 2020; Wamukota, 2009). On the other hand, we believe the fisher's perceptions that the port will provide them with job prospects are unlikely to happen. Our findings show that most fishers' education falls short of the minimum requirements for adapting to better and formal positions at the port (Cinner et al., 2018, 2015). Unfortunately, politicians and leaders responsible for gaining fisher support for these projects sometimes foster this idea, ignoring the poor education level of the local community and the difficulty of obtaining such job prospects (da Costa Oliveira et al., 2016).

The poor engagement of fishers in decision-making for the port development, as evidenced by the fisher's response, was a crucial outcome of our study. We find that this engagement was low, because some of the fishers that were part of this study were not consulted throughout the port's development process. Moreover, it could also be possible that while some fishers were consulted, the engagement was not meaningful because their concerns were not considered. An informal talk with one of the Lamu fisheries officers corroborates the lack of consideration of fishers in interests in the decision-making process. The officer mentioned that some disagreements have happened between the fishers and the port administration, because of the insufficient amount of compensation offered due to port impacts and payment delays (personal communication). Hence, the fishers strong stance against port development may have resulted from poorly handled compensation procedure. However, since a large majority fisher respondents said they were not consulted, it is highly likely that there were insufficient number of consultations held. While some forms of the consultation were carried out, we believe these consultations did not engage the fishers in more meaningful discussions. These discussions could include properly presenting the potential impacts of port development, ways to minimise and manage these impacts, and different approaches to compensate and support fishers that will be displaced and affected by the port.

While both Kenya and Tanzania have legislations that guide development projects, which include stipulations that require stakeholder participation in planning processes, our results showed that the participation of the fishers from Lamu and Bagamoyo in port planning and decision-making processes was minimal and showed discrepancies in the application of the relevant policies. The Environmental Management and Cooperation Act (EMCA) of 1999 in Kenya, and the Environmental Management Act (EMA) No. 20 of 2004 in Tanzania are the anchor legislations for undertaking Environmental Impacts Assessments (EIA) and strategic environmental assessments (SEA). Currently, these laws are used to guide ocean development and public engagement in each country. However, several obstacles still prevent effective public engagement in environmental decision-making, which include inaccessible information that contributes to the lack of public understanding of stakeholders' duties and rights during EIA and SEA processes, incomprehensible language in proposed project proposals, and insufficient regulations for public engagement during SEA are all issues (Okello et al., 2009). These obstacles need to be addressed and should also include building the capacity of BMUs and their leaders so that they can properly represent fishers in the development process. Increasing the capacity and the role of BMUs will also be advantageous, because they can improve the engagement of fishers in future ocean development projects in both countries (de Mattos et al., 2022).

Addressing policy gaps, strengthening and properly implementing existing policies to assure social fairness, equitable benefit distribution, and stakeholder participation can help protect the rights of people and affected communities, help develop trust between the stakeholders involved and effectively manage ocean development (Bennett et al., 2019; Cohen et al., 2019). Since the blue economy is based on sustainable ocean development, it emphasises the importance of increasing human well-being and social fairness apart from lowering environmental dangers and ecological scarcities. (United Nations, 2014). Many countries have embraced the blue economy concept and developed relevant policies that align with their national development plans (Wenhai et al., 2019). Currently, Tanzania has a blue economy for the autonomous region of Zanzibar, while Kenya is still yet to create have a blue economy policy (Hafidh et al., 2021). Given the importance of SSF in the region, the SSF Guidelines that FAO member states ratified in 2014 might be a valuable resource to utilise in the blue economy policy-making process to align future policies with the requirements of SSF (Jentoft, 2022)

Marine spatial planning (MSP) is another crucial instrument that African nations are using to boost the blue economy (AU-IBAR, 2019). It entails mapping and assigning marine space for various users and objectives (Ehler et al., 2009). The MSP process emphasises stakeholder participation, equitable sharing, and sustainable use of resources (Ehler et al., 2009; Ntona and Morgera, 2018; Pomeroy and Douvere, 2008), and can be utilised with the blue economy policy to protect the rights and interests of small-scale fishers, ensure socio-economic justice, and meaningful stakeholder participation in the ocean development process. Several African countries, including Kenya, have MSP initiatives at different stages of development (Ehler, 2021). This serves as an important opportunity that can reduce disputes between fishers and other users, and lower pollution that could harm SSF if activities are well planned (Jentoft, 2022; Jentoft and Knol, 2014).

5.0 Conclusion

Small-scale fisheries is a very important sector in East Africa that supports the livelihood and food security of coastal communities. Ocean grabbing, environmental degradation, loss of livelihood, and a lack of inclusivity in decision-making are some of dangers and risks posed by the recent increase in maritime development operations. Governments must take action to treat small-scale fishers fairly and to include them in ocean governance so that fishers can have sustained access to marine resources and livelihoods. This study employed interactive mapping through group discussions and community perception surveys to investigate and describe the perceptions of fishers in Lamu and Bagamoyo on the impacts of port development. Our results show that fishers in both study areas have been negatively impacted by port development, which have contributed to the increasing concerns about the survival of SSF. Currently, port activities have displaced fishers and contributed to the degradation of nearshore coastal habitats and reduced fish catch. While some fishers believe the port expansion will open new markets and job prospects, which may be true to some extent as with other port cities, these opportunities might not be that favourable to the Lamu and Bagamoyo fishers due to their lower levels of education and capacity. Moreover, we found gaps in governance in both Kenya and Tanzania, which limits fishers' engagement in decision-making processes that contributes to injustices in the implementation of the blue economy.

To address these gaps, we propose three approaches to help increase the representation of SSF in the blue economy of Kenya and Tanzania, and potentially the entire East African region. First, small-scale fishers should have access to correct information about ocean development projects and proper representation in decision-making processes, such as the EIA and SEA, to help them make informed decisions and the space to voice their concerns about such projects. Second, Kenya, Tanzania, and the other East African countries should adopt blue economy policies that have safeguards for SSF, such as the FAO SSF recommendations, to ensure sustainability of SSF and protection of the rights of small-scale fishers. Lastly, MSP has been recommended and increasingly being able to demonstrate its utility in developing spatial management plans that can guide ocean development. Since MSP also strongly promotes stakeholder participation, it can help ensure proper representation of SSF and protect the interests of fishers.

This research, which builds on other studies such as Okafor-Yarwood et al. (2020) and Rodden (2014), is one of the first studies that described and critically analysed the impacts of port development on SSF and the power imbalances in various sectors within the blue economy discourse. It is important that more research should be done to understand the extent and complexities of SSF and ocean developments interactions, and to evaluate policy gaps, interactions, and implementation to increase fairness and achieve blue justice in East Africa.

3.3 Case study 3. The extent of IUU fishing and the role of governance in the Indian Ocean.

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Keywords: Illegal, unreported, and unregulated (IUU) fishing, Indian Ocean, Governance, vessel monitoring system (VMS), automatic identification system (AIS), fishing effort

Abstract

Illegal, unreported, and unregulated (IUU) fishing is a significant global issue that potentially impacts marine fish stocks and ecosystems. This study analyses unreported fishing activities in the Indian Ocean (IO) basin for the longline fishery. Estimates of the extent of unreported fishing activities were done by comparing fishing effort data reported to the Indian Ocean Tuna Commission(IOTC) with data analysed by the Global Fishing Watch. We also investigate the role of governance in mitigating IUU activities in the region. We estimate that 54% of longline fishing activities are unreported, with the highest prevalence in the basin's Northeast region. An estimated 136,000 metric tonnes of fish worth 0.26 bn is unreported annually by longliners in the IO. Regional differences in unreporting positively correlate to the countries' governance levels surrounding those regions. This creates a vicious circle where developing countries' inability to afford monitoring control and surveillance equipment may promote IUU activities, further depriving them of significant economic benefits. Inaccurate fish statistics are a potential threat to sustainable management fisheries, especially the billfish taxa, primarily caught by the longline fishery, indicating the need to accelerate IUU measures in the region. There has been some success in cubbing IUU in some IO regions; our approach could help accelerate the fight against IUU

1. Introduction

Illegal, unreported, and unregulated (IUU) fishing is a significant issue facing marine ecosystems globally (Detsis et al., 2012; Sumaila et al., 2006). It takes several forms, including unreporting or underreporting of fishing activities, fishers fishing in areas they are not authorised to fish, or fishing fish species considered endangered and illegal to fish (Riskas et al., 2018; Sumaila et al., 2006). IUU fishing has substantial adverse effects on the environment and the socio-economic aspects of coastal states, including threats to the conservation of marine biodiversity and loss of revenue by coastal states (Cooperation, 2008; Riskas et al., 2018; Sumaila et al., 2006). Therefore, it is widely accepted that measures should be undertaken to end IUU globally. Consequently, the international community has prioritised efforts to end IUU. The United Nations (UN), under its Sustainable Development Goals (target 14.4), had intended to end illegal by the end of 2020. However, significant challenges in identifying and stopping IUU fishing made this goal unattainable, including a lack of studies (Long et al., 2020; Schmidt et al., 2017).

Most of the research on IUU has been on the loss of endangered species, fishing in protected areas, trafficking in humans and illicit goods, with unreported fishing getting minimal attention despite its obvious negative impacts on the marine socio-ecological system. Unreporting and under-reporting of fishing activities threaten food security and socio-economic stability, especially for countries that depend highly on fisheries for food security and foreign exchange earnings. For example, if the total catches reported are lower than the actual catches, states may be misled to offer higher quotas, leading to overfishing the fish species (Rudd and Branch, 2017; Van Beveren et al., 2017).

Fishers must report to countries' fisheries management bodies for regionally managed fisheries taxas like Tuna and Billfish. Subsequently, countries’ fisheries management bodies are obligated to report to Regional Fisheries Management Bodies (RFMOs). However, due to insufficient monitoring control and surveillance structure, many fishing activities are unreported (Agnew et al., 2009; Pauly and Zeller, 2016; Sumaila et al., 2006). It is estimated that close to 53% of the catch is unreported globally (Pauly and Zeller 2016). There is a clear need to intensify studies quantifying IUU activities, especially at regional and local levels, to help fisheries management bodies place proper measures such as harvesting limits.

Most of the IUU fishing activities have been linked to poor governance. Countries experiencing higher political instability, corruption, and the inability to regulate trade have a high level of IUU activities (Agnew et al., 2009; Doumbouya et al., 2017). These governance issues encourage IUU activities in several ways. First, political instability may encourage foreign fishing vessels to fish without permission. Second, corruption and lack of transparency enhance the ability of foreign vessels to acquire false licenses allowing them to fish in those regions. Third, areas experiencing poor governance are also economically poor, making it challenging to develop efficient Monitoring, control, and surveillance (MCS) mechanisms such as Vessel Monitoring Systems (VMS) (Doumbouya et al., 2017; Glaser et al., 2019; Yan and Graycar, 2020). In the Indian

Ocean, gaps still exist in understating the relationship between governance and perpetuating IUU fishing activities necessary for directing ocean management.

Assessing IUU activities IUU fishing activities is complex, and methods are varied. One of the standard methods is the use of "anchor points", which are scientific estimates for a single year and sector in a fishing area and interpolation for the periods with missing data based on available data such as commercial fisheries (Agnew et al., 2009; Forrest et al., 2001; Pauly and Zeller, 2016; Pitcher et al., 2002). Other used approaches include catch and trade data, surveillance data, expert opinion and surveys (Donlan et al., 2020; Pitcher et al., 2002). These methods still have some limitations. For example, the anchor method's application is complex, with data missing or of low quality. Surveillance data from equipment such as the Vessel Monitoring System (VMS) may not be accessible in some countries due to high installation costs and lack of technological capacity to manage the system (Detsis et al., 2012). The paper suggests a cheaper way of assessing IUU activities based on this background.

Currently, several fisheries datasets can be used to provide a basis for evaluating IUU. We explore the use of the Indian Ocean Tuna Commission (IOTC) fisheries data and the Global Fishing Watch (GFW) Automatic Identification System (AIS) data to identify and quantify IUU activities. The IOTC database has valuable fishing effort data running since the 1950s and is currently considered the base source for knowing how much and where Tuna targeting vessels fished. Catch and effort data are reported by countries to IOTC in numbers or weight, and effort as the number of hooks deployed given by 5 degrees and 1-degree grid area and month strata (IOTC, 2010). On the other hand, AIS provides information on vessel positioning, which can be used to map some fishing activity independently or together with VMS/Logbook data (Kroodsma et al., 2018). AIS was initially introduced by the International Maritime Organization (IMO) to support marine safety, i.e., avoiding ship collisions by broadcasting vessel position and other information to nearby vessels. IMO requires a mandatory AIS installation only for vessels exceeding 300 GT. Some countries have also adopted AIS for vessels operating in their national jurisdiction and recent studies have indicated that most longline fishing vessels are equipped with AIS devices (Crespo et al., 2018; Kroodsma et al., 2018).

Our research aims to contribute to the growing body of knowledge on the extent of IU activities and the role of governance in the IO region. In this study, fish catches for three years (the years for which both GFW and IOTC data were available) for the Indian Ocean Region's longliners fleet are used to estimate the unreported fishing activities. We compare the GFW effort data as a base data collected regularly, with minor external influences and errors with the data reported to the IOTC. The specific objectives of the study are (1) to analyse and quantify the difference between the fishing effort identified by GFW and the fishing effort reported by fishing vessels to IOTC; (2) to show Spatio-temporal patterns in the distribution of fishing effort unreporting; (3) to translate unreported effort into the volume of unreported catch and its associated economic value; and (4) to quantify the relationship between unreported fishing and regional governance indices.

2. Materials and methods

2.1 Data

Whereas IUU fishing encompasses broader aspects, including illegal, unreported and unregulated fishing activities, our analysis focuses on the unreported fishing activities. We also focus on longliners whose fishing activities are mandated to be reported to the IOTC, the regional organisation responsible for managing Tuna and Tuna-like species in the IO. Fisheries data, i.e. effort (number of hooks per country per month) and catches (Total weight) were obtained from the IOTC database (https://iotc.org/data/datasets). The data is reported to IOTC in a gridded format at 5° ×5° by month, year, and grid, based on countries' reports on their vessels operating in the region.

AIS data for 2016-2018 were obtained from the GFW website (https://globalfishingwatch.org). The spatial dataset contains estimated fishing effort through intensities (hours of fishing) at a 10km grid per day resolution. Our analysis of the datasets included merging CSV files, mapping the global data set, clipping it to the study area, and gridding the data in ArcGIS 10.5. key parameters obtained included date, vessels ID (mm), fishing position, Effort (hrs), flag, vessel class and gear.

2.2 Identification of unreporting by comparing effort datasets.

The IOTC effort data is reported at 5° ×5° per month, while vessels aggregate the GFW at a 10Km grid. We created the same strata for GFW and IOTC data by aggregating GFW effort data up to the IOTC data scale for comparing the two datasets. The resultant comparison scale was on a

5° ×5° grid reference for each month over three years. We classified fishing as “unreported” based on identifying any 5° ×5° cell-month where GFW reported effort, but IOTC did not. We marked only the absence of IOTC effort data to classify a cell as either “reported” or “unreported”. Table S1 is a part of the final table for analysis, showing the reported and unreported data of the 4 top fishing countries.

2.3 Spatio-temporal variations in unreporting

We divided the Indian Ocean Basin into four spatial areas (NW, NE, SW, and SE) (Figure 1). The boundaries of the four spatial areas follow the IOTC 5◦ ×5◦ grids, so no grids overlap the spatial areas. These demarcations are commonly used by the IOTC for stock assessment purposes, as indicated by differential abundance and depletion levels among regions for most IOTC priority fish species and fishing activities distribution.

2.3 Estimating the catch and value of unreported fishing effort.

We use the IOTC reported catches to translate our estimates of unreported effort into the unreported catch. We assume the total IOTC unreported catches to the reported catches will equal the unreported fishing effort's ratio to the reported effort. The estimate of unreported IOTC catches, therefore, is calculated as:

$$Catchunreported = \frac{Effortunreported * Catchreported}{Effortreported}$$

The fished value was calculated using globally fisheries price data obtained from the FAO Yearbook of fishery and aquaculture statistics (G. S. FAO, 2020). The prices used were for the tunas, bonitos, and billfish group, which corresponds to the species considered in this study and is shown in table (S3).

2.4 Linking governance to illegal activities

We utilise World Bank Governance Indicators to test governance's role in illegal fishing activities across international boundaries in the Indian Ocean region. We use government effectiveness, political stability, and wealth as governance indicators to measure the relationship between governance and unreported fishing activities. We use the world bank governance indicators for 2018 available at http://info.worldbank.org.

3. Results

3.1 Spatio-temporal variations in unreporting

Our analysis is confined to the areas where there was no reporting to the IOTC by countries for that grid and month. Therefore, our estimation of unreporting represents the lowest possible estimate of unreporting in the region. Longline fishing activities in the IO are spatially structured, with most fishing activities occurring in the NE and SW regions (Figure 3.3.1). On average, the level of unreporting of fishing effort for IO is estimated at 54%. However, spatial-temporal variations were identified in the unreporting of fishing activities in the region. The highest level of unreporting was found in the NW region, with an average of about 63% of unreported fishing efforts. Simultaneously, the region with the least levels of unreporting was the SE, with an annual average of 41% unreported fishing efforts between 2016-and 2018. The three-year average indicates that the amount of unreported fishing effort is increasing in the NE regions. In contrast, the other regions have almost similar unreported fishing activities over the study period (Figure 3.3.1).

The top fishing countries' unreported fishing efforts varied across the four regions. Comparing the level of unreporting by the top 10 fishing countries in the IO, Taiwan had the highest level of unreported fishing effort, followed by Seychelles and Sri Lanka. While Taiwan's unreported fishing activities were found across the four regions, unreported longline fishing activities by vessels with Seychelles and Sri Lanka flags were restricted to the NE and NW regions.

At the same time, countries such as Japan, Korea, and Portugal show a high level of reporting in all the regions (Figure 3.3.2).

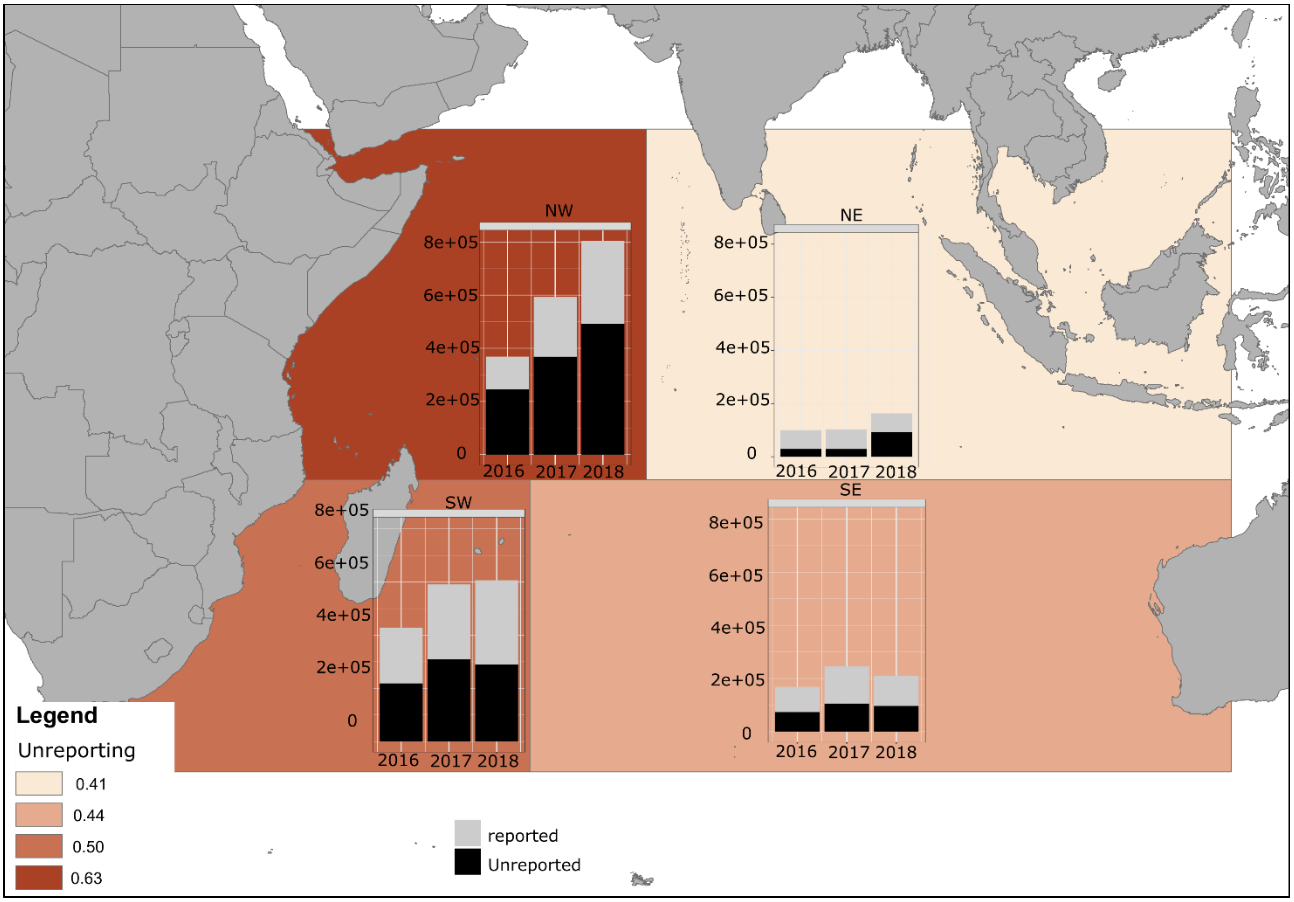

Figure 3.3.3: Proportions of reported and unreported (Data that was or was not in grids that were reported to IOTC) GFW fishing effort, 2016–2018

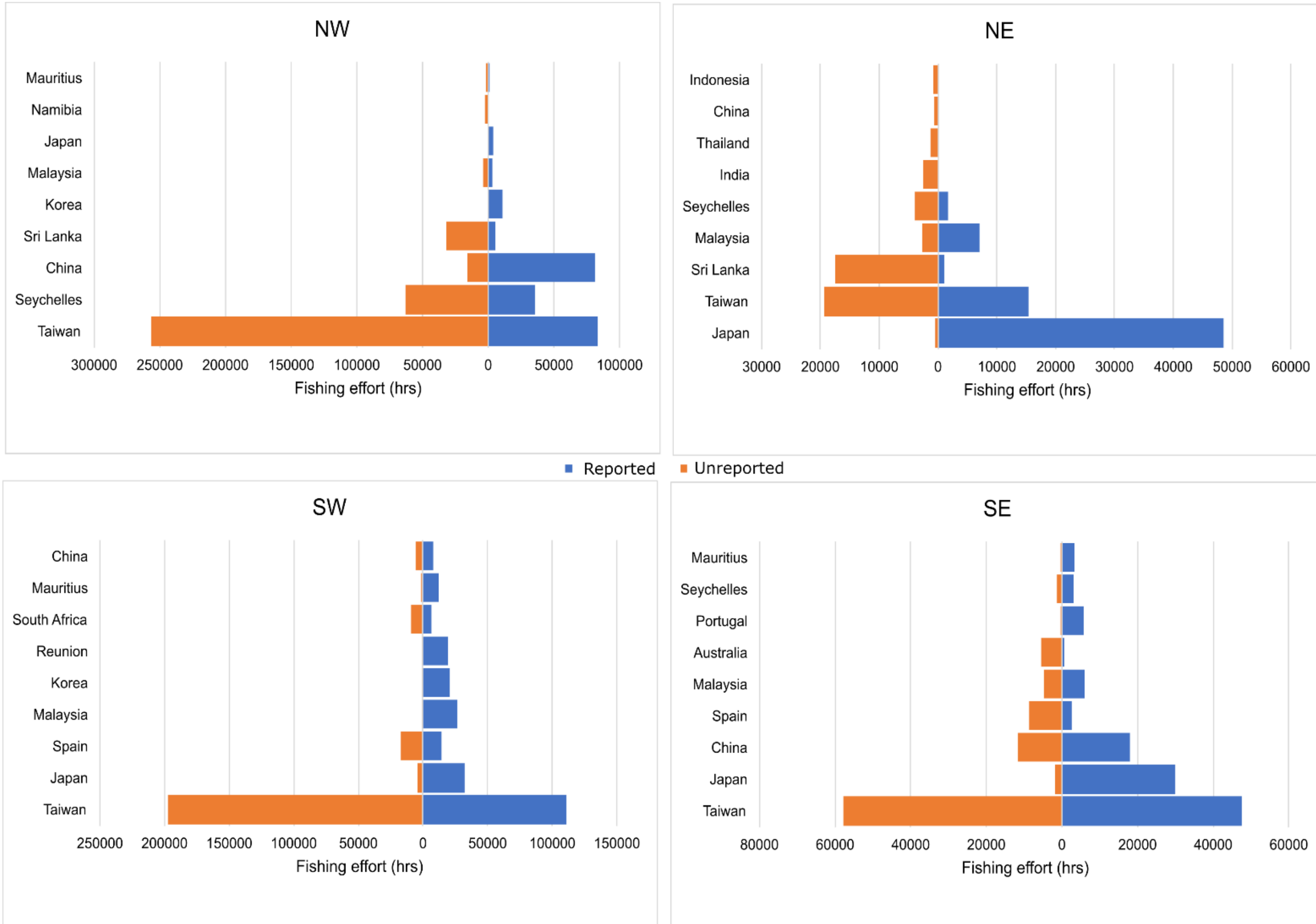

Figure 3.3.4: Unreporting of fishing effort by countries. Total 2016-2018

3.2 Catch and value of unreported fishing effort.

We estimate that the overall annual amount of Tuna and billfish unreported catches for longlines is about 136 000 MT tonnes worth $256 million. The number of unreported catches follows the spatial trend of total effort and unreported fishing effort. Most unreported catches were in the NE region, and the least unreported catches were in the NE region. Although the NE region had the highest level of unreporting, the catch values for the three indicate that both the total catches and unreported catches have been decreasing over the three years (Figure 3.3.3).

The decreasing trend of total catches and unreported catches in the NE regions is opposite to the total effort and unreported in this region. (Figure 1,3).

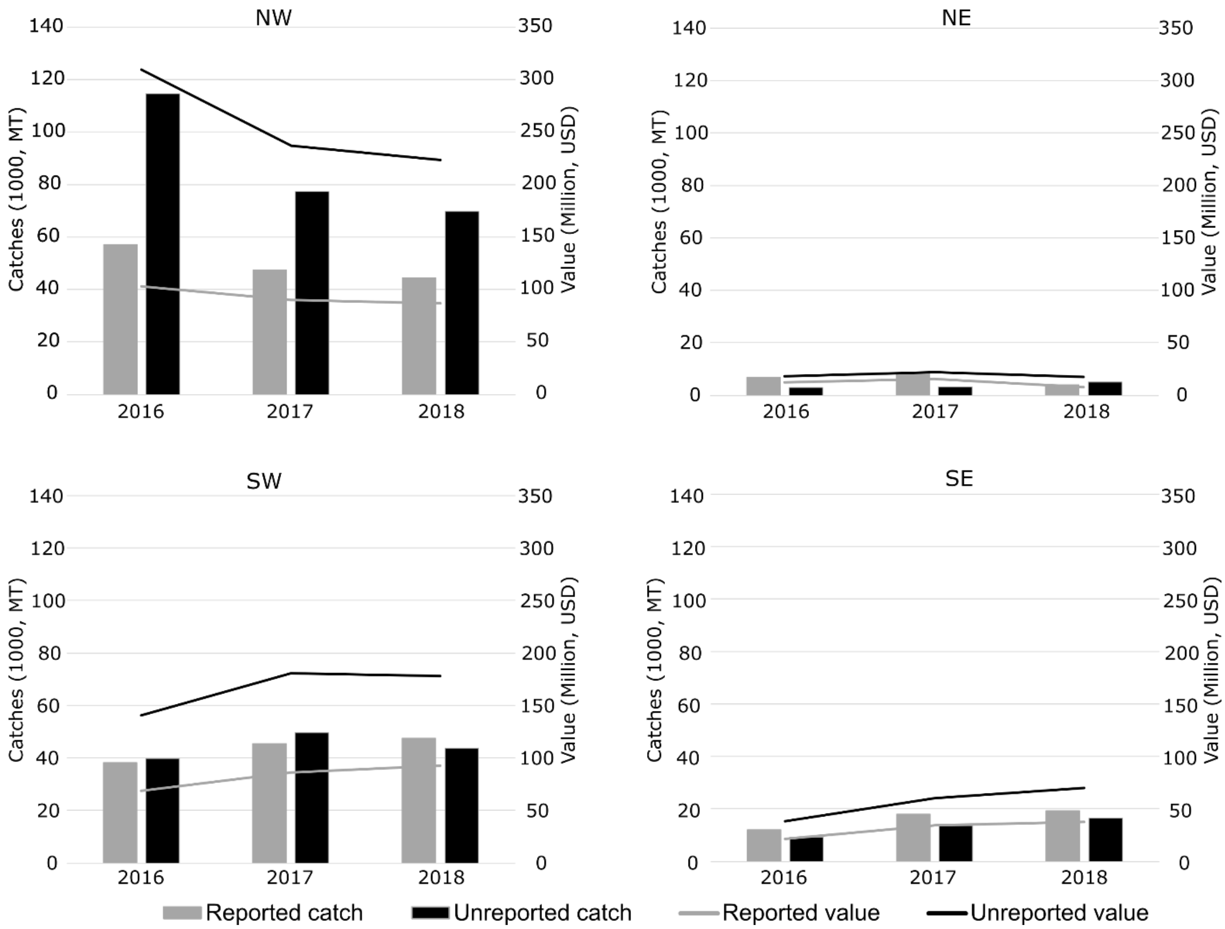

Figure 3.3.5:Estimated unreported fishing catches and value for the 3-year study period.

3.3 Relationship between unreported fishing and governance

We found a significant relationship between unreported fishing activities and the measured World Bank governance indicators. Regions with a high index of political stability, government effectiveness, Regulatory Quality, Rule of Law, Control of Corruption and GDP had a low level of unreporting (Figure 3.3.4,5)

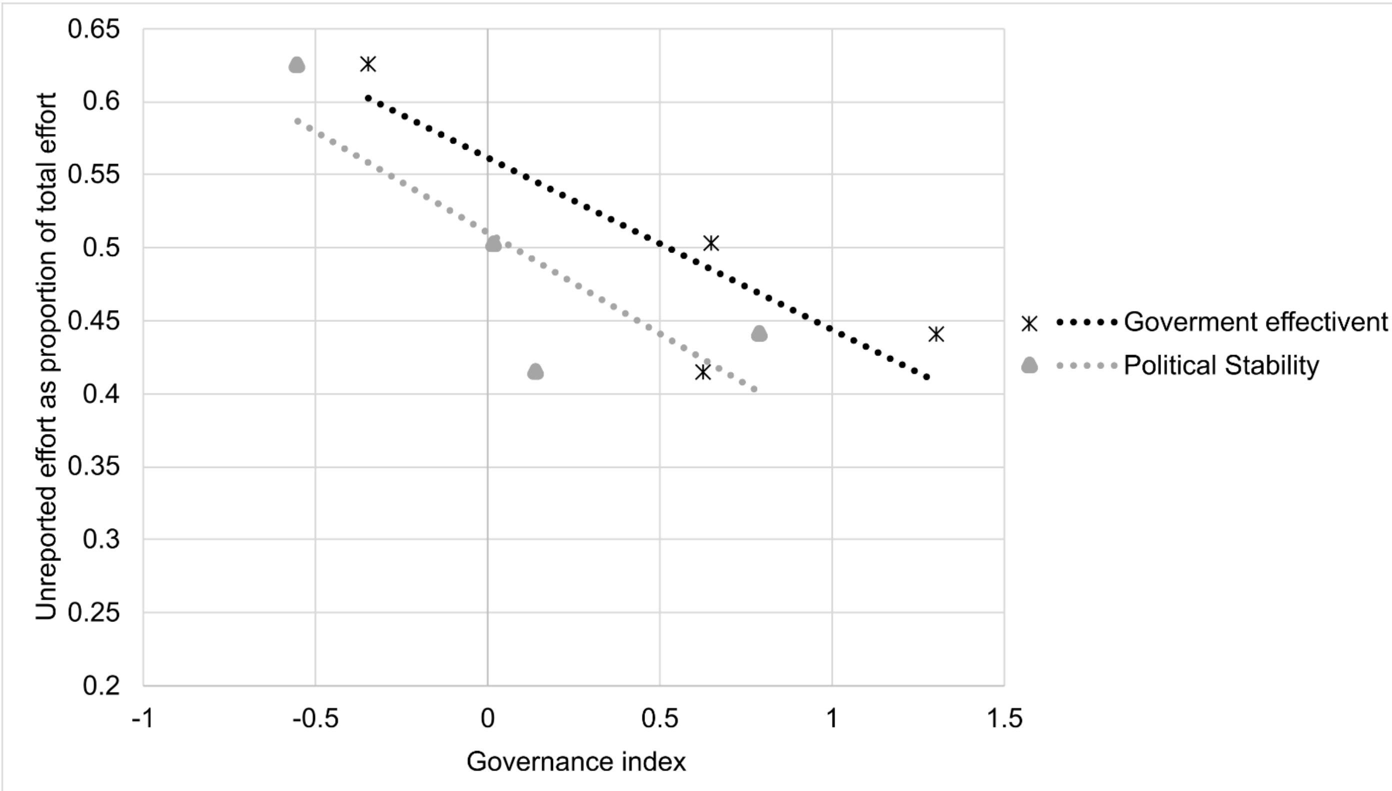

Figure 3.3.6:Relationship between the amount of unreported fishing (Proportion of the unreported effort to the total effort) and the average World back indices for each region).

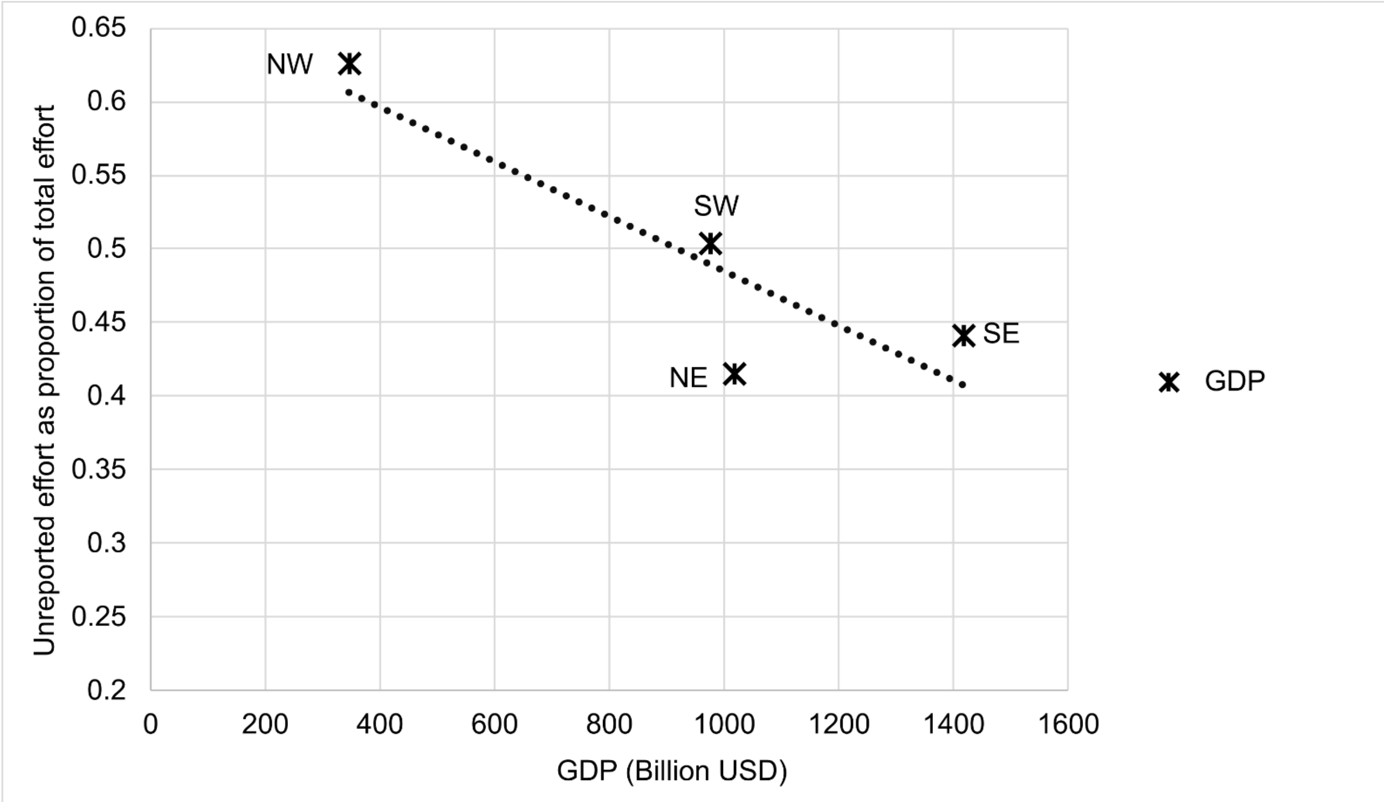

Figure 3.3.7:Relationship between the amount of unreported fishing (Proportion of the unreported effort to the total effort) and the GDP for each region).

Discussion

Our study investigated the current extent of unreporting by longline fishing vessels in the Indian Ocean and exposed the possible economic losses experienced by countries. We also test for governance's role in perpetuating unreporting fishing activities in the region. Our finding exposes a high level of un reporting, currently estimated to be above 54% of the current reporting levels, implying that countries may be losing a lot of revenues in licences. Further, our study reveals a significant correlation between governance and the level of unreporting of fishing. More impoverished regions have the highest unreporting fishing activities, indicating double jeopardy and a vicious circle. Poor coutries with little resources to monitor their resources are also the most prominent financial loser in resource management.

Overall, our presents demonstrate new information on the level of un reporting experiences in the Indian Ocean regions, Which will be essential for managing fish stocks in the Indian Ocean region. The overall unreporting level of 54% is similar to the global IUU level, estimated at 53% (Pauly and Zeller, 2016). The Spatial structuring of unreported fishing efforts informs the crucial areas where management can enhance MCS initiatives. The NE region presents an area where most fishing activities and unreported fishing efforts occur in the IO. This region has recently been one area with the most extensive illegal fishing operations (Kilgour and Copeland, 2020). The consistency of work and that of (Kilgour and Copeland, 2020) Indicate that this region should be given a preference for IUU operation by fisheries management bodies.

In contrast, the adjacent NE region has a much lower level of unreporting. Governments in this region, such Indonesia have recently have implemented aggressive policies to curb the high levels of IUU fishing in this area that have previously been done by foreign fishing vessels (Cabral et al., 2018). Our analysis points to high governance indices as probable reasons for the low unreporting level in this region, results which are also backed by findings from recent studies.

The temporal trends of unreporting in the region are also worth noting; our results indicate increasing fishing activities increase, especially in the NW and SW regions. This trend can be interpreted in several ways. Fishing activities in the NW region have declined since 2005 due to the increase in piracy (Chassot et al., 2012; Okamoto, 2011). The current increase in unreporting in the area corresponds to the increase In fishing activities in the area, which may be due to a recent improvement in security measures to curb piracy (Belhabib et al., 2019). Another possible cause of the increase in unreporting is the result of the increase in vessels installing and using AIS transponders on their vessels and fishing gears, which are the only ones that can be analysed using our methodological approach (Kilgour and Copeland, 2020). Our analysis only included the longline fishing vessels, which are much larger, and most of the vessels have AIS equipment installed (Crespo et al., 2018a).

IUU fishing is a multifaceted issue with possible implications for marine ecosystems' social, economic, and ecological aspects (Lindley and Techera, 2017). Whereas the biggest motivation for illegal fishing is the economic gains, most of the negative impacts of IUU are economic and ecological damages to the ecosystem. Our analysis indicates that 136,000 MT of Tuna and billfish species is unreported by longline fishing vessels. Longline fisheries present about 7% of the overall Tuna catches in the Indian Ocean region (IOTC, 2020b). The biological effect of un reporting may not be immense for Tuna. However, longliners' reporting may impact other species primarily caught by longliners, such as billfishes (IOTC, 2018). Specifically, the swordfish, blue marlin and striped marlin have about 70% of their catch from the longline fishery. These three species are particularly in danger from the un reporting activities of longlines. Recent stock assessments on these species indicate that the blue marlin and striped marlin are overfished while stock(IOTC, 2019). Our analysis indicates that these species' actual catches may be way higher than the set catch limits proposed by IOTC, which puts this species at a much higher risk of overfishing. The specific possible impacts of unreporting on these species' stock status are beyond this study's scope.

The economic implications of IUU fishing activities presented by our study are three-fold. First, the operation model for longliners, mostly foreign fishing vessels in the region, is based on the host country's licensing agreement with the foreign operating states. These agreements usually come with fishing quotas meant to help the species' sustainable exploitation. For example, the Republic of Seychelles has agreed to €2.5 million in payment for the right to access Seychelles' fisheries up to 50,000 tonnes by EU purse seiners longliners(Salifa, 2020). IOTC sets limits for setting quotas for the Contracting Parties Members (Noye and Mfodwo, 2012). The under-reporting of fishing effort and catches means that countries are losing money, as fishers catch more than agreed. Second, the establishment of the Quotas for countries is based on historical catches, and Lower historical catches lead to the provision of higher Quotas, which will lead to overexploitation of depleted stocks continually and lead to a decline of term economic gains in the long run(Belhabib et al., 2019). Lastly, the Billfish fisheries by foreign fishing vessels may shift their fishing effort to other areas. However, the ultimate losers are small-scale and sports fishers in the coastal areas who will lose income when fish stocks are depleted (Belhabib et al., 2019; Kadagi et al., 2020).

Our study strengthens the outcomes of recent studies such as those (Agnew et al., 2009; Belhabib et al., 2019, 2015) that political instability, lack of governance, high corruption, and little transparency increases the level of unreporting and other forms of IUU. Fishing activities by foreign vessels are rarely recorded and reported because of the lack of MCS in the region. The ability of poor coutries to sustain proper MCS activities such as VMS and observer programs cannot be overlooked. MCS activities are costly; poor coutries cannot afford the MCS, making them vulnerable to economic losses by IUU fishing, producing a vicious circle that further reduces and makes these coutries poorer (Kelleher, 2002). Enhancement of MCS activities coupled with harsh penalties has proved successful in some parts of this region (Cabral et al., 2018). Our study approach is applicable and timely for the region. It is specifically suited for countries that don't have access to high-cost technologies such as the VMS by comparing AIS data with the obligatory IOTC database. Our approach could benefit the IOTC to enhance compliance by the IOTC members.

We acknowledge several limitations to the study; For example, there is an indication that global capture fisheries decline due to anthropogenic effects such as climate change and overfishing (Pauly and Zeller, 2016). Therefore, an increase in fishing effort may not be directly proportional to an increase in catches, especially for fished stocks above the MSY(Caddy and Mahon, 1995). However, we note that the estimated unreported catches are on the lower sides and are comparable to other studies of unreported catches (Agnew et al., 2009; Belhabib et al., 2015; Pauly and Zeller, 2016). We only computed unreporting as the GFW data in an area where the IOTC data was missing; in reality, more underreporting may also be happening in the area where both GFW and IOTC data. Therefore, the unreported catches may be higher than those indicated in this study. There is an opportunity for this methodology to be improved if fisheries management bodies adopt it. For example, in comparing the data's unreporting, we did it per country flag, which is the level when data is reported to the IOTC; in this case, we cannot pinpoint which vessels are solely responsible for the unreporting. This can quickly be resolved if the analysis is done using dataset acquired at the vessels level and could give a more accurate account of the unreporting activities.

Despite the shortcoming of estimating the exact extent of unreporting, these findings affirm that IUU fishing in the IO is still high. Our methodological approach could be used to create bases in 1) identifying culprit countries with a history of submitting inaccurate datasets to the RFMOs and 2) Identifying areas with more likelihood of IUU fishing activities. The study contributes to SDG Goals (target 14.4) by increasing knowledge of the extent of IUU fishing in the IO. This is a significant step in bringing a more holistic understanding of the IUU problem and improving fisheries management in the IO. We are pointing out that the NE is a hotspot of the IUU activities by the longline fishing vessels. The IOTC should work together with other RFMOs such as SWIOFC and the National government to extend the management of the longline fishing activities in this region.

3.4 Case study 4. AIS and VMS Ensemble Can Address Data Gaps on Fisheries for Marine Spatial Planning

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Keywords: vessel monitoring system (VMS); automatic identification system (AIS); marine spatial planning; data coverage; fishing effort

Abstract:

Spatially explicit records of fishing activities' distribution are fundamental for effective marine spatial planning (MSP) because they can help to identify principal fishing areas. However, in numerous case studies, MSP has ignored fishing activities due to data scarcity. The vessel monitoring system (VMS) and the automatic identification system (AIS) are two commonly known technologies to observe fishing activities. However, both technologies generate data with several limitations, making them ineffective when used in isolation. Here, we evaluate both datasets' limitations and strengths, measure the drawbacks of using any single dataset and propose a method for combining both technologies for a more precise estimation of the distribution of fishing activities. Using the Baltic Sea and the North Sea–Celtic Sea regions as case studies, we compare the spatial distribution of fishing effort from International Council for the Exploration of the Seas (ICES) VMS data and global fishing watch AIS data. We show that using either dataset in isolation can lead to a significant underestimation of fishing effort. We also demonstrate that integrating both datasets in an ensemble approach can provide more accurate fisheries information for MSP. Given the rapid expansion of MSP activities globally, our approach can be utilised in data-limited regions to improve cross border spatial planning.

Introduction

Increasing demand for marine ecosystem services globally has led to increased pressure on marine ecosystems and competition for space among various marine uses (Bastardie et al., 2015; Halpern et al., 2008). To address the effects of pressures on marine areas, managers are considering more holistic management approaches to managing maritime spaces (Gee et al., 2011). Marine spatial planning (MSP) is one of the main tools for a holistic management of marine resources. MSP involves allocating marine space for different uses considering the areas' suitability, impacts on the environment and possible conflicts between activities (Ehler et al., 2009). MSP is a data-intensive process, for which outcomes are susceptible to the inherent data uncertainties. Among the steps for implementing MSP Ehler et al., (2009), defining and analysing the existing and future conditions requires high-resolution spatio-temporal data on the various marine uses (Eastwood et al., 2007).

Fisheries are among the marine uses with the most spatially extensive and temporally heterogeneous pattern. However, there has been some deficiency in the coverage of fisheries issues in MSP partly due to the unavailability of fisheries spatial data (Fock, 2008). In regions where MSP is being developed or implemented, spatial planners have mostly relied on the vessel monitoring system (VMS), logbook data (Campbell et al., 2014; Shucksmith et al., 2014) or used qualitative methods such as interviews and participatory mapping to identify principal fishing areas (Turner et al., 2015). The advantages of using VMS over other methods is that it is often mandatory for fishing vessels operating in national waters to have VMS. As a result, VMS data are usually very consistent. When combined with logbook data, VMS provides a reliable estimate of the spatio-temporal distribution of fishing activities (Amoroso et al., 2018; Hintzen et al., 2012; Russo et al., 2014). However, VMS has several challenges such as high installation costs, and encryption of the VMS signals, which means that only the government agencies can access the data. Additionally, the low VMS data broadcasting frequency makes it challenging to identify fishing activities at a finer spatiotemporal scale (Hintzen et al., 2012; Russo et al., 2016; Shepperson et al., 2018). Overall, these challenges have made it difficult to deploy VMS as a tool for measuring fishing effort data in many parts of the world(Taconet et al., 2019).

The recent advent of the automatic identification system (AIS) for mapping fishing effort distributions has provided an opportunity to fill the existing gaps in spatial fisheries data for MSP. AIS was initially introduced by the International Maritime Organization (IMO) to support marine safety, i.e., avoiding ship collisions by broadcasting vessel position which can be used to map fishing activity independently (Ferrà et al., 2018; Kroodsma et al., 2018) or together with and other information to nearby vessels. AIS provides information on vessel positioning, VMS/logbook data (Russo et al., 2016). Recent analysis indicates that there is high potential for AIS to be a primary source of mapping fishing effort globally. Its main advantages are low costs and ease of accessibility compared to VMS data (Kroodsma et al., 2018; Taconet et al., 2019).

VMS and AIS differ in several ways: the mode and frequency of satellite signal transmission, the coverage of the fishing vessels and the accessibility of data. VMS signals are transmitted from the vessels to ground stations only. In contrast, AIS signals can be received by other ships nearby, by ground stations and by satellites (Taconet et al., 2019). Additionally, AIS has a high-frequency vessel position transmission with a current average of about 30 s in some regions (Shepperson et al., 2018; Taconet et al., 2019). Consequently, the data is highly temporally resolved and better suited for mapping fishing effort compared to VMS. The main shortcoming of AIS is that it is not mandatory for smaller vessels <300 GT. IMO only requires a mandatory AIS installation for vessels exceeding 300 GT. Additionally, larger vessels sometimes intentionally switch off the AIS for safety purposes, such as preventing piracy, and some areas do not have good AIS receptions, especially far from harbours (Russo et al., 2016; Taconet et al., 2019). Some countries have also adopted the use of AIS for vessels operating in their national jurisdiction. For example, since 2014, the EU has required vessels with a length of >15 m to be equipped with AIS. For VMS, the rules also depend on national laws. For example, in the EU, it is a requirement for fishing vessels with a length of >12 m to be equipped with VMS (EC, 2009).

Evidently, both VMS and AIS have strengths and weaknesses. Combining both data sources to leverage their strength and reduce uncertainties inherent in either system would strongly benefit a more precise analysis of fisheries patterns as a basis for MSP. The integration of the VMS and AIS data can be achieved in several ways. For example, AIS datasets could provide spatial data where VMS data are not available due to proprietary issues. Additionally, VMS data can be used to fill the gaps of AIS data in areas where there is low AIS satellite coverage, e.g., in areas further offshore, while AIS could be used to improve the temporal coverage of the fishing positions

(Malarky and Lowell, 2018; Russo et al., 2016; Shepperson et al., 2018). However, these integration mechanisms have not been implemented at large spatial scales to facilitate regional studies.

In this study, first, we investigate the possible discrepancies between VMS data provided by the International Council for the Exploration of the Seas (ICES) and the AIS data provided by Global Fishing Watch (GFW) for mapping the distribution of fishing effort at a regional level, with the Baltic Sea and North Sea–Celtic Sea regions as case studies. We test for differences in spatio-temporal patterns of the ICES VMS and GFW AIS and compare the results from the two regions. Second, based on the identified discrepancies, we suggest a method for correcting potential errors in the estimates of fishing effort. Lastly, we quantify the discrepancies when ICES VMS and GFW AIS are used in isolation compared to a combination of the two datasets.

2. Material and Methods

2.1. Data

Our study focuses on the Baltic Sea and the greater North Sea–Celtic Seas regions (Figure 3.4.1), where we were able to access long term VMS and AIS datasets. These datasets have been crucial for the development of MSP, as countries are required to pro-duce marine spatial plans by 2021 (EC, 2014).

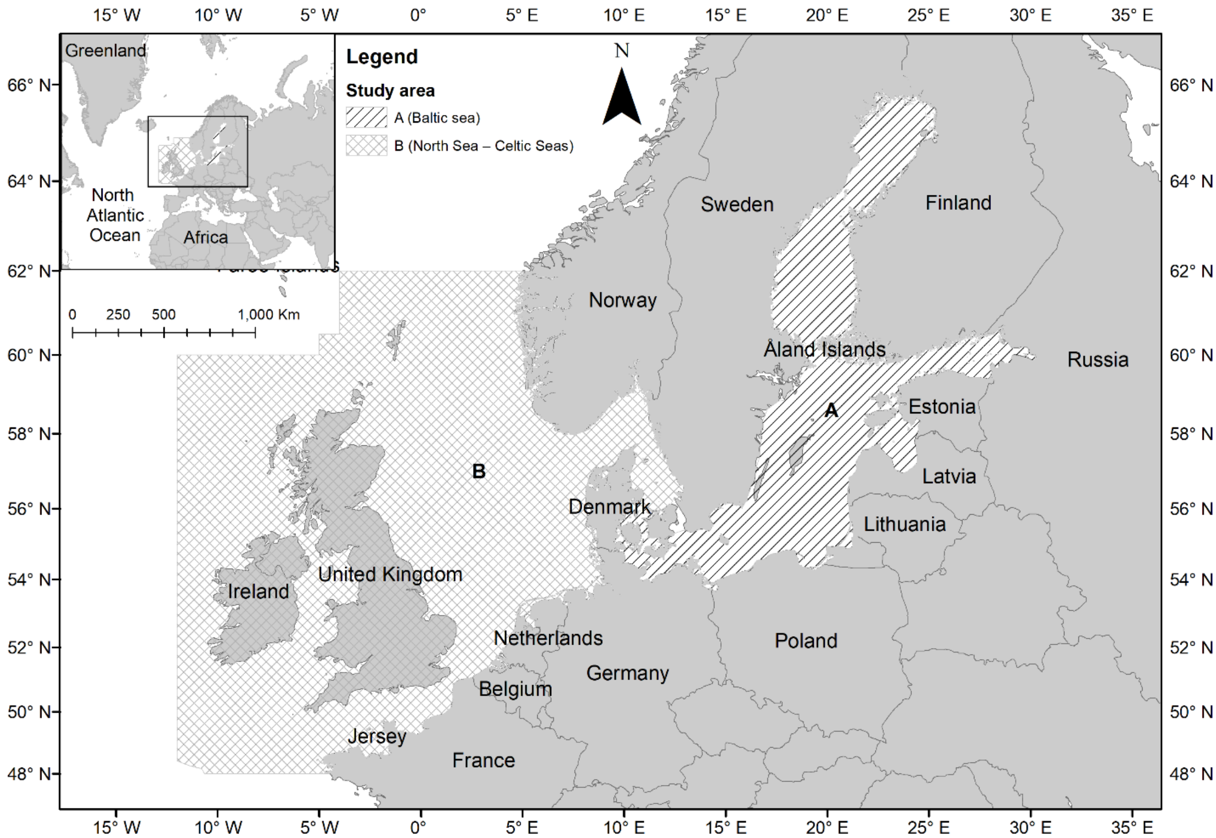

Figure 3.4.1. Map of the study area, indicating the Baltic Sea (**A**) and the North Sea–Celtic Seas region (**B**).

2.1.1. ICES VMS Data

VMS is a satellite-based monitoring system that consists of a GPS receiver coupled with a communication device. Logbooks are records of catch and effort. Usually, VMS and logbook data are combined to estimate fishing effort, but they are independent. The system is usually established by national governmental authorities or Regional Fisheries Management Organizations (RFMOs) for control and surveillance purposes. The system uses GPS technology to broadcast vessel positions to encrypted databases at authorities' monitoring them. In the Baltic Sea and the North Sea regions, VMS data are archived and analysed by ICES (ICES 2016).

We obtained processed VMS data for the period 2012–2017 from the ICES website (http://www.ices.dk). For the Baltic Sea, we used data from the Baltic Marine Environment Protection Commission (HELCOM) regions (ver.2, 22 January 2019); ICES data product release, http://doi.org/10.17895/ices.data.4684. For the North Sea–Celtic Seas region, we used data from the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR commission) regions II and III (ver. 2, 22 January 2019) http://doi.org/10.17895/ices.data.4686. The spatial data layers represent estimated fishing intensities/pressures by fishing métier at a resolution of c-squares (0.05 × 0.05 degrees). For uniformity with the AIS data, the VMS fishing effort was converted to a resolution of 10 km degrees by summing up the original 0.05° × 0.05° grids within each of the 10km grids. We combined the fishing effort data for all available métiers.

2.1.2. GFW AIS Data

AIS data for the period 2012–2017 was obtained from the GFW website (https://globalfishingwatch.org). The spatial dataset contains estimated fishing intensities (hrs) at a resolution of 10 km grid cells. We combined the fishing effort data for all available métiers. The analysis included merging CSV files, mapping the global data set, clipping it to the study area, and gridding the data to 10 km grids in ArcGIS 10.5.

Unlike previous studies [13,14], we did not analyse raw VMS and AIS datasets but already processed and publicly accessible datasets that are easy to acquire and often utilised in MSP processes.

2.2. Spatio-Temporal Variation in VMS and AIS Data

To evaluate the degree of discrepancy between ICES VMS and GFW AIS data for mapping fishing effort in the Baltic Sea and the North Sea–Celtic Sea regions, we used the SPAtial EFficiency metric (SPAEF) introduced by (Koch et al., 2018). SPAEF is a multi-composite and statistical metric that considers the differences in co-location, variation, and distribution patterns. It robustly evaluates similarities in spatial patterns (Koch et al., 2018; Plet-Hansen et al., 2020). SPAEF values range from 0–to 1, with 1 being the highest spatial similarity between the spatial distributions.

SPAEF is calculated as

Equation 1

$$SPAEF = 1 - \sqrt{(\alpha - 1)^2 + (\beta - 1)^2 + (\gamma - 1)^2}$$

where

α—is the correlation coefficient between the ICES VMS grid values and GFW AIS grid values

β—is the coefficient of variation for ICES VMS grid values divided by the coefficient of variation for GFW AIS grid values, and

γ—is the match of the histograms of the ICES VMS and GFW AIS grid values.

2.3. ICES VMS—GFW AIS Ensemble

Our approach to developing an AIS—VMS ensemble focused on the availability of AIS and VMS data. VMS and AIS have different limitations and strengths (Table 3.4.1). An ensemble of these datasets is expected to enhance spatial fisheries data accuracy and coverage (Russo et al., 2016; Shepperson et al., 2018; Taconet et al., 2019). Low availability of AIS data is mostly caused by inadequate AIS satellite coverage and deactivation of the AIS transmitter by the fishing vessels in areas where AIS use is not required by law. VMS data availability is low in areas where the system has not been installed or where data is not available due to proprietary issues. Hence, in areas where either VMS or AIS is lacking, the datasets' combination can help improve the overall spatial data coverage.

Table 3.4.1. Strength and weaknesses of automatic identification system (AIS) and vessel monitoring system (VMS) datasets (adopted from [13–15]).

	VMS	AIS
Strengths	• High vessels coverage as it is mandatory to use for fishing vessels in some jurisdictions with penalties for switching off • Good signal reception in most places and hence consistent data availability • High confidence for identifying vessels and their fishing activity due to the availability of logbook data	• High temporal frequency of fishing position data • Open-source data, easily accessible to the public
Weaknesses	• Low temporal frequency of fishing position affecting the estimation of fished area • Data availability is restricted to specific national agencies	• Low vessels coverage as it is not mandatory for use by fishing vessels • Low signal reception in some areas and hence inconsistent data

It is important to note that the GFW AIS and ICES VMS fishing intensities are estimated with different methodologies(Eigaard et al., 2016; Kroodsma et al., 2018). We argue that, although the ICES VMS and GFW AIS data are computed differently, the ratio of the two datasets should be the same in the grid cells where both ICES VMS and GFW AIS were recorded as they represent fishing effort for the same vessels. We use the relationship to compute the fishing effort in the cells where either ICES VMS or GFW AIS was missing, similar to the geographic ratio analysis suggested by (Duan and Bastiaanssen, 2013).

We calculated the ratio of VMS and AIS for each grid cell and averaged the ratios to obtain the overall VMS to AIS ratio for each year, as shown in Equation (2), where $E_{(ratio)}$ is the overall ratio for the year, EVMS is the VMS fishing effort (hrs) for the grid cell, E(AIS) is the AIS fishing effort for the grid cell, and N is the number of grid cells that had both AIS and VMS data for that year.

Equation 2

$$E_{(ratio)} = \frac{\sum_{i=1}^{N} \left(\frac{E_{(VMS)}}{E_{(AIS)}} \right) i}{\mathrm{N}}$$

In areas where there was either ICES VMS or GFW AIS only, we used the $E_{(ratio)}$ to derive ICES VMS or GFW AIS, as shown in Equation (3) where D (VMS) denotes the derived VMS values. The final ensemble layer was created by merging the original VMS layer with derived VMS values.

Equation 3

$$D_{(VMS)} = E_{(AIS)} * E_{(ratio)}$$

3. Results

3.1. Spatio-Temporal Variations in ICES VMS and GFW AIS Data

We identified discrepancies in the spatial-temporal coverage of fishing activities by the VMS and AIS datasets. In the Baltic Sea, in the early years (2012 and 2013), VMS data displayed high spatial coverage of fishing areas with fishing effort covering about 96% of the study area and decreasing to about 48% of the study area between 2014 and 2016 (Figure 2).

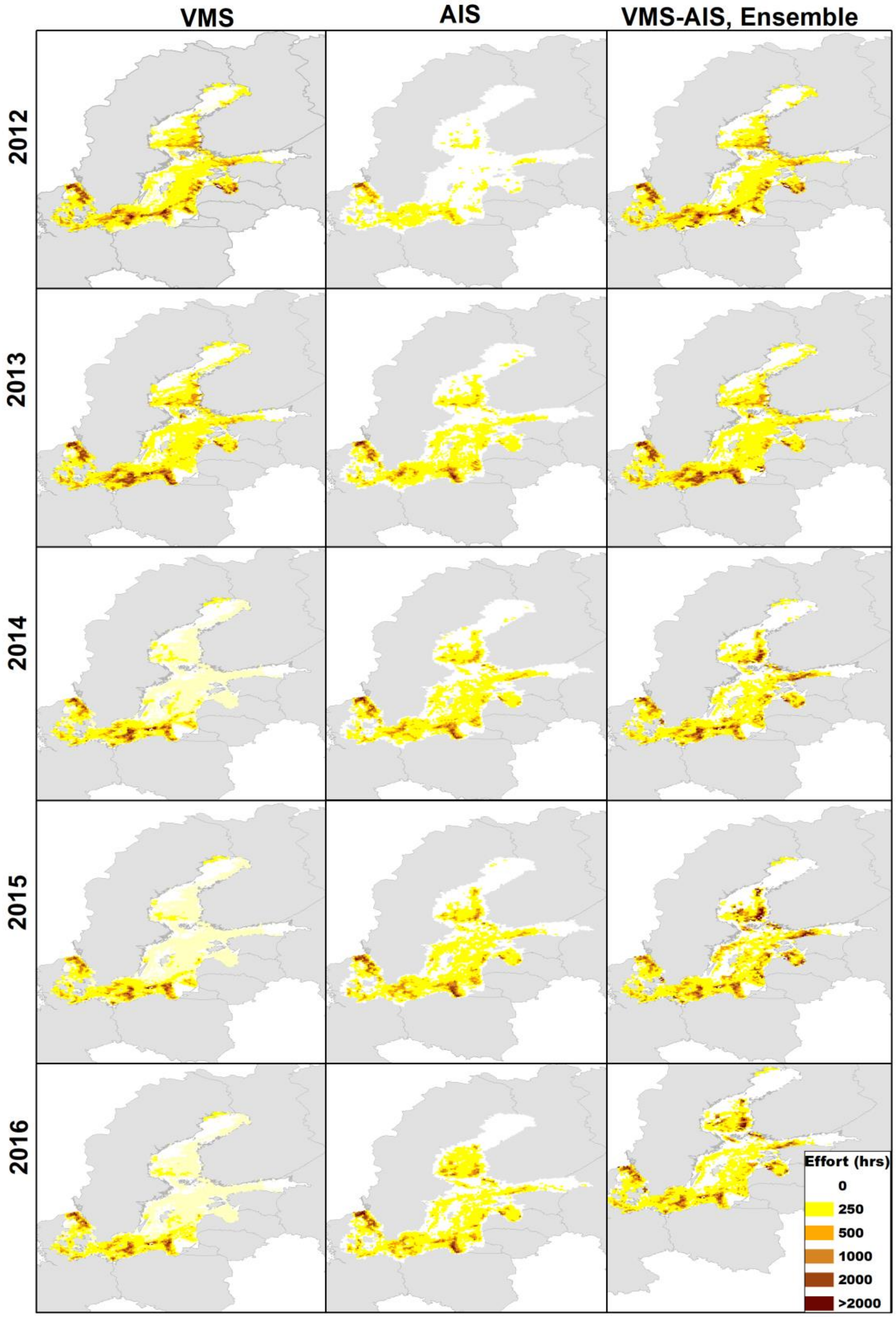

Figure 3.4.2. Spatial distribution of fishing effort (hrs) in the Baltic Sea between 2012 and 2016, using VMS and AIS datasets.

In contrast, AIS data had a low spatial coverage in 2012, covering approximately 43% of the study area, but steadily gained coverage of fishing areas, covering 95% of the study area in 2016. The ensemble data filled the VMS data gaps between 2014–2016 and restored the distribution similar to values in 2012. The ensemble fishing effort data suggests fishing activities over the entire Baltic Sea with fishing hotspots in the Kattegat and Western Baltic. The most apparent discrepancies are in the northern Baltic, which has only VMS data in 2012 and only AIS data in 2016 (Figure 2).

For the North Sea–Celtic Seas region, the VMS and AIS datasets mainly show discrepancies in 2012 and 2013, where AIS shows lower coverage than VMS (Figure 3). The ensemble datasets also show fishing activities distributed in the whole study area. Fishing hotspots were evident near the coasts of France, Belgium and the Netherlands, as well as the United Kingdom and the English Channel (Figures 3.4.3 and 3.4.5).

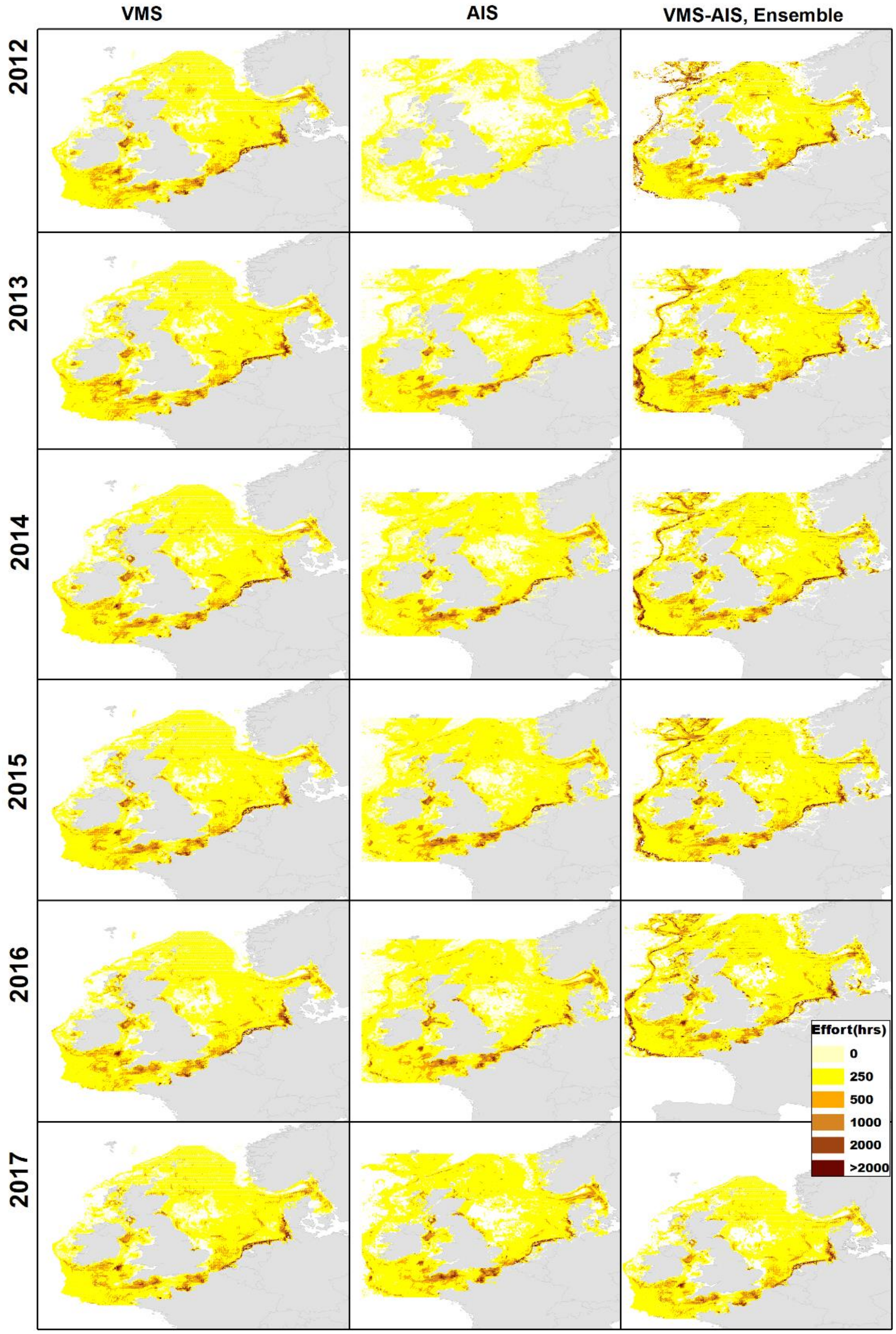

Figure 3.4.3. Spatial distribution of fishing effort (hrs) in the North Sea–Celtic Seas region between 2012 and 2017 using VMS and AIS datasets.

We found some variation in the SPAEF coefficient between annual VMS and AIS datasets between the Baltic Sea and the North Sea–Celtic Sea. Higher SPAEF coefficient was found for the North Sea–Celtic Sea (mean value 0.64), compared to the Baltic Sea (mean value 0.43) over the study period. Higher SPAEF coefficients indicate that the VMS and AIS were more similar in the North Sea–Celtic Sea region than in the Baltic Sea. Additionally, the SPAEF coefficient varied between the years. For the Baltic Sea, the lowest SPAEF value was found for 2012 and the highest for 2013. For the North Sea–Celtic Sea region, we derived the lowest SPAEF value for 2012 and the highest in 2015 (Figure 3.4.4).

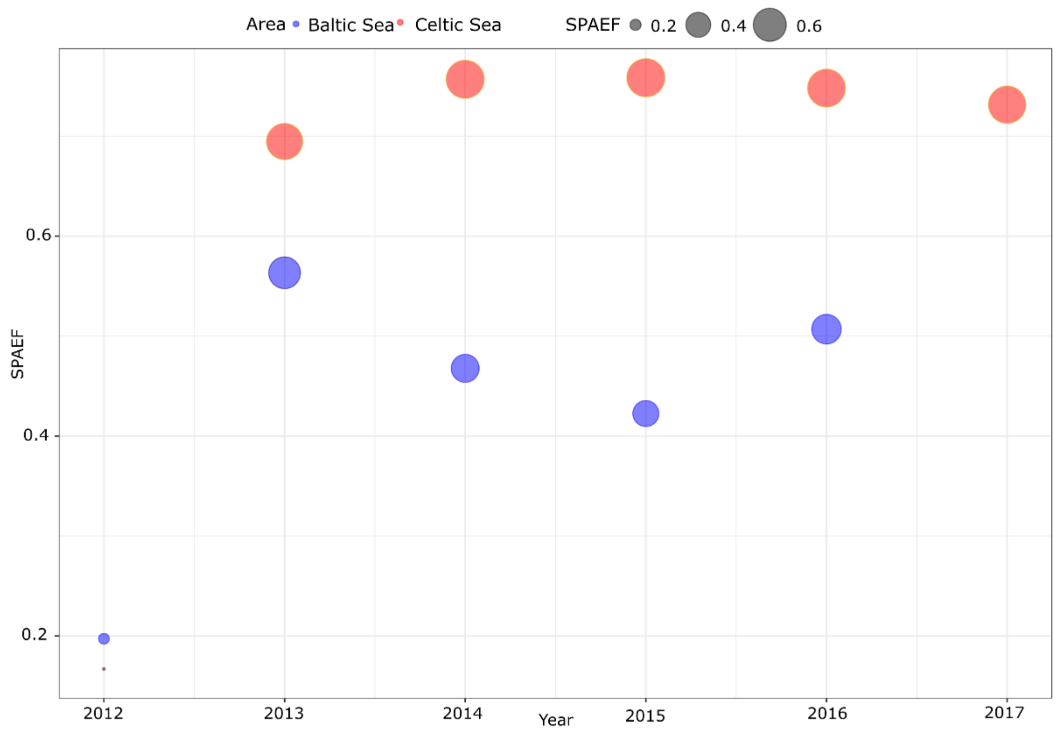

Figure 3.4.4. SPAEF values indicating the similarities of spatial patterns of the International Council for the Exploration of the Seas (ICES) VMS and GFW AIS data for the Baltic Sea and North Sea–Celtic Sea regions.

3.2. Underestimation of ICES VMS and GFW AIS Data

Our results indicate that when either VMS or AIS is used in isolation, there is an underestimation of fishing effort levels in the Baltic Sea and the North Sea–Celtic Sea regions. The levels of underestimation of fishing effort vary across the years and between the regions. For the Baltic Sea, there is a decreasing trend of underestimation of fishing activities by the AIS data over the years, while underestimation by VMS data is increasing. Similarly, there is a decreasing trend of underestimating fishing activities by the AIS data for the North Sea–Celtic Sea region over the years. However, the precision of VMS data is almost constant (Figure 3.4.5).

Additionally, Figure 3.4.5 depicts the total fishing effort's temporal trends when both the ICES VMS Data and GFW AIS data are combined to create an ensemble. Despite variations in both VMS and AIS datasets between 2012 and 2017, the computed ensemble data shows that the total fishing effort remained relatively constant during the same study period in the North Sea–Celtic Sea region, while the Baltic Sea region shows a decreasing trend over the years (Figure 3.4.5).

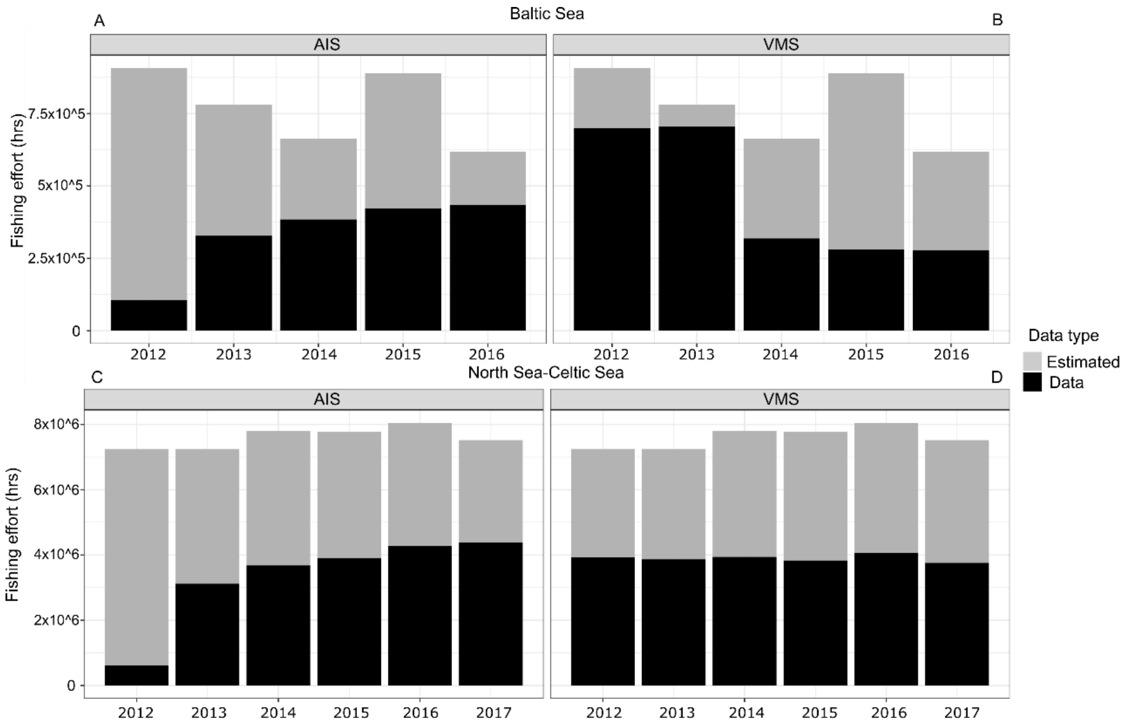

Figure 3.4.5. Total calculated fishing effort (hrs) in both study regions using the ensemble approach. Estimated data is the data derived in an area where either VMS or AIS data was missing.

4. Discussion

We investigate the discrepancies in spatio-temporal patterns of the ICES VMS and GFW AIS datasets and the potential underestimation of fishing activities when either VMS or AIS datasets are used alone to map fishing effort. The study's overall goal is to present a dataset that will show the accurate picture of the fishing effort distribution to provide more reliable data for the MSP process, especially at a regional level. We achieved our goal by inspecting the relationship between the VMS data and AIS data, interpolating this relationship for grid cells where one of the datasets was missing and creating an ensemble dataset. Such an approach is beneficial in MSP processes as it provides better evidence of fishing effort distribution.

Our findings show spatial similarities and differences between the VMS and AIS datasets in the Baltic Sea and North Sea–Celtic Sea regions. Although the VMS data and AIS datasets are computed differently, their remarkable similarity, especially in the North Sea–Celtic Sea region, indicates that the two datasets represent similar fishing effort. However, the ensemble data generally indicate an underestimation for both VMS data and AIS data. Our results confirmed that the ensemble data improve the spatial representation of fishing effort by VMS and AIS. Thus, the suggested ensemble method offers a solution for improving spatial fisheries datasets compared to a single use of either VMS or AIS data.

There are several possible explanations for the spatial-temporal discrepancies and underestimation of the VMS and AIS datasets. The large increase in AIS data in both the Baltic Sea and the North Sea areas between 2012 and 2014 may result from the improved adoption of AIS after the EU passed the law for the mandatory AIS installation for vessels of >15 m. Additionally, AIS data may suffer from poor signal receptions, especially in the area further offshore. On the other hand, the displayed low VMS data coverage observed between 2015 and 2017 in the Baltic Sea could have resulted from the non-submission of VMS data to ICES by countries in the regions (ICES. 2016b, n.d.; Kroodsma et al., 2018; Shepperson et al., 2018; Taconet et al., 2019). Our finding of a close resemblance of annual patterns of fishing activities presented by VMS and AIS data in the North Sea–Celtic Sea area as indicated by the SPAEF values is similar to recent studies in nearby regions that found a close relationship between VMS and AIS datasets in the neighbouring regions of the Bay of Biscay and Northeast Atlantic (Fernandes et al., 2019; Gibin et al., 2019). The close relationship between the VMS and AIS in the studies mentioned above was attributed to VMS's mandatory requirement for fishing vessels and high coverage of AIS in vessels of >15 m in this region.

The ensemble data approach is especially relevant in data-poor regions where MSP and conservation and planning efforts are sometimes forced to use proxies to fill data gaps (Ban et al., 2009; Gissi et al., 2018). Although the Baltic Sea area is considered to have adequate coverage of both VMS and AIS, the ICES website's accessed data had some gaps. Interestingly, VMS data alone in the area suggest reduced fishing activities in the Northern Baltic Sea areas during 2014–2016, a result not supported by AIS data during the same period. The computed ensemble data gives a better representation of the fishing effort activities of the area. The ensemble data have also provided an opportunity to redefine long-term fisheries spatial data estimates for the study area and give a more comprehensive spatial-temporal account of the spatial distribution of fishing effort than what is currently available to the public. The HELCOM map data service http://maps.helcom.fi/website/mapservice/, which covers the study area, is one of the main sources of MSP data utilised by MSP stakeholders. This data displays the same fishing effort with the data gaps as described in this paper. Our study indicates a considerable under-estimation of fishing effort activities when this dataset is used, and its inclusion in decision-making processes such MSP could hence be misleading. Additionally, to continue using this dataset for management purposes, our study helped understand its effectiveness in mapping fishing effort and what proportion of the fishing activities may be omitted.

The MSP process presents potential benefits to the fisheries sector, e.g., protecting crucial fisheries areas such as spawning and nursery grounds. However, several limitations to fisheries can also arise from the MSP process, such as reducing fishing space, modifying fishing behaviours and loss of revenue (Bastardie et al., 2015). Proper integration of fisheries in MSP depends on the availability of adequate spatial data on fisheries (Janßen et al., 2017). In some cases, fisheries data limitation has hindered the MSP processes in two steps: analysing existing conditions and planning for future activities. Ultimately, this has led to fisheries' omission in the spatial plans [6,30]. Several decision-support tools and algorithms have been developed with a good capacity of informing MSP. The ability of these tools to produce useful results is dependent on good spatial and temporal information(Gissi et al., 2018; Pınarbaşı et al., 2017; Stelzenmüller et al., 2010) . Lack of spatial fisheries data may be inevitable in some areas due to confidentiality and lack of coverage. Our approach of combining AIS and VMS improves fisheries spatial datasets' quality and can enhance MSP decision support tools' performance and ultimately improve MSP processes.

Our study utilised datasets from open sources with several limitations, such as non-submission of data and poor signals. These factors create a scenario of a data-poor area and the possibility of evaluating how the VMS-AIS ensemble could improve VMS datasets in data-poor regions. However, it is important to note that the VMS datasets in national agencies' custody may have a better quality that could be close to the one achieved by the proposed ensemble.

Eventually, our results show that combining VMS and AIS datasets greatly improved coverage in areas where differences existed and exposed the risk of fishing effort underestimation when VMS and AIS datasets are used singly. The proposed method presents an approach that could be utilised for effective cross border MSP in areas where data limitations exist.

Chapter 4. Discussion

The Canadian Fisheries Research Network (CFRN) fisheries sustainability framework suggested by Stephenson et al., (2018) is used in this thesis work to as a lens to highlight fisheries sustainability challenges and opportunities from four case studies in the IO. The four-pillar CFRN fisheries sustainability framework covers ecological, economic, social, cultural, and institutional/governance areas.(Stephenson et al., 2018). In addition, each pillar contains a set of objectives that were utilized to classify the challenges. Productivity and Trophic Structure, Biodiversity, Habitat & Ecosystem Integrity are among the ecological pillar's objectives. Economic viability and prosperity (sustainable wealth), access and benefits distribution, regional economic benefits to communities, and sustainable livelihoods objectives fall in the Economic pillar. Sustainable communities, ethical fisheries, and health and well-being are among the goals of the social pillar. Legal obligations, particularly to Indigenous peoples, good governance structure, and effective decision-making procedures are all part of the institutional pillar's goal(Stephenson et al., 2018). This section includes a case-by-case analysis of the issues and opportunities identified in the case studies, as well as a mapping of those challenges and opportunities into the CFRN sustainability framework. Table 4.1.1 shows an overview of the challenges from the case studies.

Table 4.1.1: A summary of he identified challenges from the case studies mapped into the CFRN sustanaibility framework

Fisheries sustainability framework		**Case Study 1**	**Case Study 2**	**Case Study 3**
Ecological	Productivity and Trophic Structure	-Declining catches Incidental -Overfished species -Mortalities/Bycatch		-Unreported data compromising stock assessments -Bycatch species more prone to under-reporting
	Biodiversity	-Species Risks in high diversity regions -Overlap between target and threatened species - Co-exploitation of species	-Impact of species from pollution -Introduction of non-native species	-Illegal fishing activities risk species
	Habitat & Ecosystem Integrity	-Important species habitat beyond national jurisdiction - Climate-change, Induced regime shift	-Impacts on nearshore habitats from pollution -the destruction of spawning grounds	-IUU activities in critical habitats compromise ecosystem sustainability
Economic	Economic viability and prosperity (Sustainable wealth)		-Reduction of fish catches -Low profits -Increased fishing costs -lack of capital to fish in deeper waters -Low fishers' education, excluding them from opportunities and representation -Lack of formal marketing structures -A large number of fishers in small areas	-Loss of licences income -Loss of foreign exchange
	Distribution of assets and benefits		-No precise mechanism for fishers' compensation -Male-dominated industry, lack of gender representation	-Loss of income for small scale fishers due to IUU
	Regional economic benefits to the community		-lack of coordinated management between fishers and other sectors -Loss of livelihood from developments	-IUU Deprives other sectors such as recreational fishers' of benefits
	Sustainable Livelihoods		-Loss of livelihood from developments -Loss of jobs with no alternatives	-lack of security leading to IUU -
Social/Cultural	Sustainable communities		-Poor earnings and fishers living in poverty -Poor civic culture -Lack of participation in a social institution	
	Ethical fisheries		-Lack of allocation of small-scale fishers' users' rights -Lack of adherence to SSF code of conduct -Lack of adherence to fisheries code of conduct	-Lack of adherence to fisheries code of conduct by foreign vessels
	Health and wellbeing		-Loss of food security and protein source -Artisanal fishers are poor, with some living below 1$ a day	-Threatened food security due to IUU
Institutional/ Governance	Legal Obligations including to Indigenous people	-Non-reporting of artisanal fisheries data -Lack of species information	-Lack of data on fishers' fishing effort and catch -No implementation of the SSF in the local fisheries laws -lack of recognition of indigenous fishers highly depended on fisheries	-Lack of clear legislation on IUU -Non-adherence by foreign vessels to local MCS laws
	Good governance structure	-Lack of comprehensive database to support management - Poorly recorded data -Lack of transparent data	-Lack of involvement of fishers in decision making -Lack of government support to fishers -	-Poor collaboration between national and regional bodies on data -Inconsistency between national and regional policies
	Effective decision-making process	- Advice based on aggregated data/IOTC data	-lack of transparency in decision making	-lack of transparency in tackling IUU issues, corruption by officials -Non-compliance

Challenges facing the fisheries sector.

Case study 1: Billfish distribution in the IO region

Billfish are a significant fishery in the Indian Ocean since they are targeted by artisanal, recreational, and commercial fishers. The case study highlighted many challenges that may influence the fisheries' sustainability from the data and the literature review. Regarding the ecological pillar, the literature assessment found that billfish catches from longlines, which account for the region's largest billfish catches, have decreased. IOTC has also classified three of the six billfish species as overfished(IOTC, 2019). The lone exception is an increase in gillnet fishers, particularly in Iran, who have seen a rise in catches. This, however, might be explained by the fact that the data collecting and reporting of the Iran gillnet fishery has improved, which could be accountable for the rise in catches(IOTC, 2019). Overall, the signs show that the species are overfished, and the fishery is seeing a fall in catches (IOTC, 2018). Maintaining the maximum production potential of major target species is critical for fisheries sustainability, and it has been noted as a challenge for the IO area in this case study(Pauly et al., 2002). The threat to species biodiversity is depicted in the findings of our study. A significant concern is that billfish species are caught alongside highly valued tuna species(Chang et al., 2019). An extra degree of challenge is provided by the fact that some of the areas with significant biodiversity of species occur outside of national jurisdiction, where there are many uncertainties engulf the management of the species, posing a serious risk to the fisheries(Crespo et al., 2019).

The primary goal of the first case study was to provide light on the ecological elements of fisheries sustainability; the economic and social pillar concerns did not emerge clearly from this case study. However, the thesis links a few challenges exhibited in the study to the institutional/governance pillar. The institutional challenges are related to the execution of laws, policies, institutional processes, and legislation. The thesis outlines a few challenges from the literature and the research methodology of the first case study. First, there is a paucity of data on major commercial species such as billfish; for example, the exploitation status of the shortbill spearfish in the region is unclear due to a lack of sufficient data to undertake population assessments(IOTC, 2019). The data from OBIS and IOTC that we assessed to perform the SDMs were also insufficient(Klein et al., 2019). For example, we attempted to analyze the influence of seasonality on billfish species using the SDM, but the OBIS and IOTC data had insufficient data to allow us to comprehensively segregate the data into the required season for the analysis. Furthermore, analyzing the data was particularly difficult since the region occurrence data is based on the OBIS database, which is a worldwide dataset with a worldwide spatial resolution(Klein et al., 2019). We were unable to locate a high-quality regional database with accurate species occurrence data for our investigation. Although the IOTC data accessed through the IOTC website had a regional focus, a couple of challenges were also encountered for this dataset, including data aggregation, a lack of data in some areas, such as the Somali region, and some inconsistency in the spatial resolution of the data, with some countries reporting a 5-degree by 5-degree resolution while others reported a 1-degree by 1-degree spatial resolution(Herrera and Pierre, 2009). The data also had some transparency issues because to the reporting being done at the individual nation level rather than the vessel level. In this instance, the ability to trace back the problem in the data as well as use the data for management purposes is limited.

When planning and developing fishery management, good quality data enable the development of the best advice for the fisheries(Simmonds et al., 2011). The data limitations for fisheries outlined here is a key setback for the IO region's fisheries sustainability. The regional organizations responsible for decision making, such as IOTC, rely on data submission from member countries; a lack of data from member countries demonstrates a lack of coordination by these regional organizations(Herrera and Pierre, 2009). The final challenge presented is fisheries decision making. As previously discussed, the data used for management is limited. Nonetheless, the use of data this is however limited. It is necessary for providing management guidance for the region; however, this data should be used with caution, as it may lead to misleading management outcomes(Klein et al., 2019). Key institutions in the region are already employing strategies to make this data useable, such as the IOTC, which raises catch data to account for data that is not reported(Herrera and Báez, 2019).

Case study 2: Impacts of port development on small scale fishers in

The primary goal of the second case study was to highlight the socio-economic challenges of fisheries sustainability in the IO. However, a few challenges surfaced that spurned across all four pillars of fisheries sustainability. The results of the literature research and our findings paint a bleak picture for coral reef fisheries in East Africa. The ecological problems are numerous. Since most of the fisheries in the region are small-scale, with fishers using low-powered boats, fishing is restricted to a small coastal area, resulting in overfishing for most species (McClanahan and Mangi, 2004; McClanahan et al., 2008; Thoya and Daw, 2019). Apart from overcrowding in the coastal area, unsustainable fishing methods such as beach seine, spear, and dynamite fishing have reduced the SSF catches in the region(McClanahan and Mangi, 2001; Slade and Kalangahe, 2015). Pollution connected with new ocean development, such as port expansion, exacerbates the issue. Recent events, such as the oil spill in Mauritius, confirm fisheries' risk from other ocean sectors (Seveso et al., 2021). Our results indicate coral reefs and mangroves, which are vital breeding and fish habitats, have been damaged by port activities such as dredging and the release of toxic wastes. Several fish species have already been declared at risk of extinction in the region because of the threat to the fishers' catches and genetic diversity(Buckley et al., 2019). The introduction of non-native species is also a major worry for the region, as evidenced by the findings. When port activities are not closely monitored, non-native species can be introduced, posing a threat to the local fish population.

This case study also highlights several economic challenges threatening the Indian Ocean region's fisheries' long-term economic viability. The case study findings can be applied to other countries in the region that are hugely dominated by small-scale fishers. According to case study findings, the fisheries' economic sustainability is in jeopardy. Because of their little capital, fishers are limited to fishing in a small, overfished coastal region (McClanahan and Mangi, 2004; Thoya and Daw, 2019). May fishers get extremely little money; according to our research, Bwagamoyo fishers earn an average of $10 per day, while fishers in Lamu, Kenya, earn $24 per day.

Given that most fishers come from a family of roughly five individuals, with fishing revenue adding to the household's higher income, this suggests that fishers are not making enough money from the fisheries to support their families. Also, because of the poor fish market, fishers are forced to sell their catch through middlemen at low prices, resulting in the intermediaries making more money than the fishers (Kimani et al., 2020; Wamukota, 2009). New developments in the near-coastal area, such as port construction, exacerbate the problem by forcing fishers to fish further offshore, rising fuel costs and diminishing profitability(Bastardie et al., 2010).

The benefits from compensations due to the fishing disruptions are not evenly spread throughout the community, raising concerns about the fishers' financial sustainability. Fishers are excluded from decision-making, and as a result, they receive little or no compensation for the losses they suffer because of these coastal developments. There is a lack of coordination between small-scale fisheries and other marine sectors that would allow for a fair negotiation when such projects arise. Low fishers' education limits them from finding alternatives such as jobs in other sectors and their ability to fully engage in the negotiation process (Cinner et al., 2018; Pita et al., 2010).

The second case study also demonstrates critical governance issues connected to the long-term sustainability of fisheries. First, there is limited information on small-scale fisheries challenges caused by recent growth in ocean developments, which is a critical aspect of developing governance. According to a recent literature review by Ayilu et al. (2022), current research and policies are more likely to place industrial-scale fisheries and aquaculture in the blue economy setting than small-scale fisheries. This is partly due to the difficulties faced by small-scale fisheries, such as a lack of data. For example, in case study 2, we were compelled to adopt participatory mapping to gather spatial information on small-scale fishermen (Daw et al., 2011).

In the case study, there are gaps in fishers' participation in the decision-making process; according to our findings, fishers in Lamu and Bwagamoyo were not well involved in the port development decision-making process. Further analysis and evaluation of the literature also indicate that the FAO SSF guidelines are not well enshrined in the current fisheries legislation in Kenya and Tanzania. The SSF guidelines that focus on preserving fishers' rights, including their involvement in decision-making, are an essential tool for the perpetuation of SSF sustainability (Kurien, 2015). Also seen in this case study is the little commitment of government agencies to solving problems related to SSF. For example, we learned that fishers in Lamu had been waiting for over two years for compensation from the government(Okafor-Yarwood et al., 2020). The thesis also reveals a lack of transparency in the decision-making process, particularly in environmental impact assessment.

Case 3: The extent of IUU fishing and the role of governance in the Indian Ocean.

The case study focuses on IUU operations in the IO and serves as an example of the region's governance and economic challenges. There are also some connections to the ecological pillars that emerge from this case study. The risk that species confront owing to illegal fishing activities in the region is one of the ecological challenges depicted in this case study. Underreporting of fishing operations may result in negative management actions, such as awarding fishing countries large quotas, leading to overfishing (Rudd and Branch, 2017; Van Beveren et al., 2017). The existence of high-productive zones in the ABNJ that contain a diverse range of species, along with a lack of monitoring, management, and surveillance, constitutes an ecological threat (Crespo et al., 2019; Dunn et al., 2018).

The socio-economic issues posed in this case study are enormous; the findings of a high degree of IUU operations result in a significant loss of money for the region's countries (IUU Watch, 2017). Countries that lose revenue have less money to spend on development and fisheries management (Glaser et al., 2019). This is particularly worrying because it creates a vicious cycle in which developing nations with no money for fisheries management efforts suffer more dangers of illegal fishing and lose even more money. This is especially true for developing countries in the region undergoing political unrest(Glaser et al., 2019). This scenario creates a threatening condition for the fishing sector's economic viability and success. Another economic challenge posed by IUU activities is the possible reduction in the catch for small-scale and recreational fishers situated along the coast, which would impact food security and livelihoods (Belhabib et al., 2019; Kadagi et al., 2020).

Several challenges connected to the social pillar of fisheries sustainability emerge from the study. Vessels operating in the region lack adherence to the fisheries code of conduct due to their incapacity to report fisheries activities to the appropriate authorities. The possible loss of food security because of IUU operations poses a threat to the region's health and well-being(Kasim and Widagdo, 2019; Poernomo, 2011).

This case study brings out several governance issues. First, the high degree of IUU activities in the region indicates a lack of ability for the national and regional organizations to conduct successfully, MCS operations(Sumaila and Bawumia, 2014; Voyer et al., 2018b). The scenario is worse in places with low governance indexes and corruption levels(Fisheries, 2015; Glaser et al., 2019; Sumaila and Bawumia, 2014). This study also reveals an insufficient collaboration in the reporting of fisheries data by countries to regional bodies like the IOTC and a lack of defined IUU rules at the international level. (Hutniczak et al., 2019). There are also weaknesses in administering IUU operations in the area beyond national jurisdiction(Voyer et al., 2018b). Overall, the issue of IUU fishing poses a significant threat to the region's fisheries' long-term sustainability.

Opportunities for a sustainable fisheries sector.

Case study 4: The AIS and VMS ensemble can address data gaps on fisheries for marine spatial planning.

The last case study evaluates the discrepancies between two fisheries' spatial data sets. It provides a method for combining the two datasets to create a superior dataset for use in management processes such as marine spatial planning (MSP). The case study highlights the importance of good spatial data for management and the importance of marine spatial planning for fisheries management.MSP is a general procedure for designating maritime areas for various purposes (Ehler et al., 2009). The approach is very participatory, with all critical stakeholders in the maritime space included(Pomeroy and Douvere, 2008a).

Putting MSP through the lens of fisheries sustainability opens a world of possibilities for sustainable fisheries management. In terms of ecological sustainability, allocating spaces for fisheries has significant advantages, such as protecting spawning and nursery grounds(Campbell et al., 2014). The creation of fisheries spaces such as marine protected areas (MPAs) supports the long-term sustainability of fisheries by preserving genetic diversity and sustaining sustainable fish populations. Fisheries closures support habitat and ecosystem integrity, which can benefit the long-term sustainability of fisheries resources (Selig and Bruno, 2010). Allocating harmful activities away from vital fisheries zones reduces pollution problems and improves fisheries' sustainability(Fock, 2008). For example, in case study 2, where there are issues of fisher-port interactions, marine spatial planning may be utilized to handle this problem.

MSP may also improve the economic sustainability of fisheries. Research has shown that geographical restrictions on fisheries can improve fisheries by enhancing neighbouring fisheries with a spillover effect (McClanahan and Mangi, 2000; Russ et al., 2003). Increased catches will help the livelihood of fishers and their families. Under the MSP process, the fishing community's economic interests are also protected. Throughout the process, MSP ensures that all stakeholders' concerns are addressed and that equity is preserved(Jentoft, 2017; Nutters and da Silva, 2012; Pomeroy and Douvere, 2008b). Compensation for missed opportunities such as a decline in catches due to project development may be addressed throughout the MSP process since the process recognizes the necessity for tradeoffs to achieve the most feasible ocean management results(Jennings et al., 2012; Yates et al., 2015). MSP is a new approach to improving marine governance that builds on the ecosystem viewpoint, which is currently at the heart of fisheries governance(Degnbol and Wilson, 2008; Vince, 2014). MSP understands the need of bringing together agreements between many institutions involved in various parts of ocean management, enabling collaboration and openness in the management process(Pita et al., 2010). Finally, MSP plans that include fisheries management objectives improve the sector's effective decision-making processes. (Janßen et al., 2017)

The use of fisheries spatial information, particularly the AIS and VMS data, is the second opportunity for fisheries sustainability that emerges from this case study. As indicated in Table 1, a lack of spatial data is a cross-cutting concern in all three cases analyzed. The VMS and AIS databases offer advantages and downsides, as illustrated in case study 4 (Thoya et al., 2021). The VMS's restrictive nature is the most significant difficulty, with access limited to national agencies overseeing the system. On the other hand, AIS is more open source and available; however, this is only mandatory for large vessels. Because the VMS system is costly for most countries, countries in the IO can use AIS to improve geographic data coverage(Taconet et al., 2019). AIS is now only necessary for boats above 300 GT in the region, which is an IMO requirement. Other regions, like the EU, mandate that boats longer than 15 meters be fitted with AIS(EC, 2009). Countries in the Indian Ocean may adopt a strategy like this to expand the region's fisheries spatial data coverage. If such a strategy is implemented, it has the potential to improve the region's fisheries sustainability significantly. Improved vessel surveillance will minimize IUU fishing, resulting in increased income from fisheries for governments. This will also help fisheries management by increasing compliance with spatial restrictions like MPAs. The use of open data for management will increase transparency among stakeholders and enhance fisheries management in general (Dunn et al., 2018).

Linking case study outcomes to Indian Ocean Blue economy sustainability.

Establishing a sustainable blue economy of marine sectors such as fisheries, aquaculture, marine transportation, port activities, and coastal tourism will be required to be ecologically sustainable, economically viable, and socially equitable(Cisneros-Montemayor et al., 2021). This thesis examined the fisheries industry's challenges and opportunities for achieving sustainable fisheries sectors. On a broader look, these experiences from the fisheries sector are applicable across other marine sectors.

Foremost, our case study reveals various concerns that impact environmental sustainability in the IO. In our second case study, we looked at the destruction of ecosystems, including mangroves and coral reefs, overfishing and illegal fishing. Environmental effects will not be restricted to the fishing sector but will also influence other blue economy sectors. For example, the loss of mangroves and coral reefs and pollution from ports will have an impact on tourism and aquaculture(Bennett and Reynolds, 1993). For any sector to be ecologically sustainable, a proper environmental impact assessment should be performed to examine the project's possible environmental implications(Hodgson et al., 2019).

Economic viability for blue economy sectors means that the activities' economic benefits exceed their economic costs(Cisneros-Montemayor et al., 2019; Pauli, 2010). For our case study, we highlighted issues that may cause the costs of fisheries to outweigh the benefits, such as a decline in targeted species owing to overfishing and an increase in fishing operation expenses, such as Lamu fishermen being forced to fish further offshore. Small-scale fishers profit financially, socially and culturally because fisheries are not solely exploited for commercial gain but also for other social and cultural advantages such as food security. The economic benefits did not make the fishery look viable in case study 2 since the fishers' income was nearly minimal. However, the fishers continued to practice the fisheries owing to other benefits such as food security. This case applies to other industries; when a project is being developed, an economic impact assessment must be carried out, considering the project's socio-economic and environmental implications(Hodgson et al., 2019). Although the Lamu port may have a significant economic impact, the environmental costs of the project, as well as the loss of socio-cultural value of the SSF, may outweigh the advantages(Okafor-Yarwood et al., 2020).

The potential outcomes of a successful of the blue economy sector include economic regeneration, secure livelihoods, food security, and community well-being(Okafor-Yarwood et al., 2020). For the long-term sustainability of the blue economy sectors, a fair distribution of benefits is critical. The system should provide opportunities to compensate for the loss of livelihoods and food security for the communities impacted by ocean developments. The thesis has highlighted key challenges that may obstruct the fair distribution of benefits from the case study, such as a lack of involvement of indigenous users and stakeholders and a lack of capacity of indigenous users, such as small-scale fishers, to participate in the decision-making process. This is a critical element to address in all sectors; development initiatives should include a method for balancing power among various stakeholders and enhancing meaningful stakeholder participation in decision-making (Bennett et al., 2019; Cisneros-Montemayor et al., 2019).

Finally, case study 4 shows the potential for MSP and open access spatial datasets to improve the fishing sector's sustainability. This also applies to other sectors; by its very nature, MSP aims to bring all maritime sectors together, assign uses where they are most feasible, and avoid disputes amongst users(Patil et al., 2018; Smith-Godfrey, 2016). As a result, MSP is relevant to all sectors and should be considered one of the major strategies for enhancing regional blue economy sustainability. Many nations in the IO, notably South Africa, Seychelles, Indonesia, Myanmar, Philippines, already have MSP or have begun the maritime spatial procedures(Ehler, 2021). If these initiatives are enhanced, this depicts a bright future for blue economy development.

Conclusions

Increasingly, the term "Blue Economy" is being used to describe efforts to ensure the long-term sustainability of maritime industries. It generally means requiring consideration of sustainability's ecological, economic, social, and institutional aspects. This is not the case; recent studies have found that the oceans are under severe stress due to new development. Implementing a sustainable blue economy across oceans requires careful consideration of national, regional, and international organizations.

Blue economy development is a new frontier that can spur development in nations with vastly underutilised marine resources. Blue Economy is gaining traction in the IO region, where many nations are classified as underdeveloped but have vast ocean resources. Several problems have been identified as impeding these efforts, including governments' apparent preoccupation with the economic components of blue economies while overlooking the environmental and social aspects, which may jeopardise the economic gains. In this thesis, emphasise is given to the challenges that various aspects of sustainability face. A sustainability framework was used to analyze four fisheries case studies and identify key obstacles and opportunities for fisheries sustainability. Following the conclusion of this step, a general overview of blue economy issues and prospects for the region is provided.

The case studies illustrate that the problems facing a sustainable fishing sector span all four sustainability elements. Pollution and overfishing will threaten the long-term viability of the fishing industry in the nearshore regions, depended on by many small-scale fishers. Lack of capital and recognition for small-scale fishers in decision-making processes intensifies the situation and casts doubt on the fisheries sector's long-term sustainability. Using case studies, we identify opportunities to transform the blue economy's fortunes using marine spatial planning, a more integrated approach to ocean management and tackling most high-level challenges. The benefits of employing low-cost data sources like AIS databases to improve fisheries management are also presented in the paper.

Looking ahead, the IO region is expected to experience increased growth in ocean-related activities. According to current indications, this development will focus on large-scale marine and transport infrastructure projects and mineral and oil resource exploitation. However, we argue that a blue economy must carefully assess the ecological and social consequences of these proposed initiatives since they have the potential to jeopardise existing sectors such as small-scale fishing, which have a significant socio-cultural significance in the region. We recommend that MSP be used to assist accommodate these new industries. The methodology utilised in this thesis is directly applicable and may be used to identify opportunities and dangers in various sectors for a sustainable blue economy. The four components of fisheries sustainability apply to all the Blue Economy sectors and are a good guide for assessing new ocean development initiatives in the region.

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Declaration on Oath

I hereby declare upon oath that I have written the present dissertation “Advancing blue economy in the Indian ocean: a case of the fisheries sector.” independently and have not used further resources or aids than stated.

Eidesstattliche Versicherung

Hiermit erkläre ich an Eides statt, dass ich die vorliegende Dissertationsschrift dissertation “Advancing blue economy in the Indian ocean: a case of the fisheries sector.” selbst verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

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