Bren School of Environmental Science & Management
UNIVERSITY OF CALIFORNIA, SANTA BARBARA

A Bioeconomic Evaluation of Distant Water Fishing Management Strategies in Liberia

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Signature Page

This Bren School of Environmental Science & Management Master's group project was completed by the project team under the direction of faculty advisor, Anastasia Quintana. It was reviewed by University of California, Santa Barbara faculty and then submitted to the Bren School for approval. This report serves as partial fulfillment of duties required for all team members to earn the degree of Master in Environmental Science and Management (MESM).

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Abstract

An abstract is required. It should provide a brief synopsis of the research and be succinct (225-250 words). The abstract should be placed following the table of contents and any optional preliminary pages (i.e., acknowledgments).

Final Tasks, Please put your name next to the tasks you are doing:

- Add figures inline and add captions and number them
- Add title, labels and and numbers to all tables - **Taylor. Cant do this yet…**
- Make final references
- ~~Make NMV table -**Taylor**~~
- Finish tasks personally tagged in **[ALL]**

Objectives

This project aims to accomplish the following objectives:

1. Evaluate the market and non-market impacts of distant water fishing (DWF), by exploring different scenarios related to DWF trawler access in Libera. Current scenarios of interest include:
    a. BAU: Business As Usual, with no change in the current amount or license agreements of DWF trawling vessels.
    b. License Access*:* Increase licensing fees by 40%.
    c. Ending DWF Trawler Access: Total elimination of any DWF trawling vessels within the Liberian Exclusive Economic Zone (EEZ) (modeled as a 100% access fee).
2. Qualitative analysis Provide a qualitative analysis for key non-quantifiable concerns to be used alongside scenario evaluation for decision-making. Topics include:
    a. Illegal, under, and unreported (IUU) fishing
    b. Human rights violations
    c. Shrimp trawling within the Inshore Exclusion Zone (IEZ)
3. Evaluate the economic, social, and environmental implications based on each scenario's expected outcomes to identify key trade-offs for government and local communities to use for decision-making.
4. Synthesize existing research on distant water fishing in Liberia, focusing on DWF trawler access and its impact on artisanal fisheries.

Project Overview

As the global demand for seafood grows, high-capacity industrial fishing fleets are increasingly operating further away from their own and largely overexploited Exclusive Economic Zones (EEZs) often in the High Seas or the EEZs of developing nations. (Berkes et al. 2006). These maritime zones extend 200 nautical miles off a country's coast and mark an area over which they have exclusive rights of use. This practice, known as distant water fishing (DWF), has intensified pressure on ocean ecosystems and the people who rely on them. It is often associated with overfishing, conflict, and illegal practices, including human and labor rights abuses (ibid; Environmental Justice Foundation 2024).

The Republic of Liberia, a coastal country in West Africa, has opened its EEZ to DWF from the European Union (EU) and China, along with private fleets, in exchange for a fee regulated through access agreements. These access agreements generate steady income for Liberia's government and the National Fisheries and Aquaculture Authority (NaFAA) (Conservation International 2023). However, DWF fleets also negatively affect Liberia's domestic fishing fleets, local communities, and marine ecosystems by overharvesting, competing for fish stocks, and damaging ecosystems through trawling via access agreements (Mechanix 2019 & Oberle 2016). Over the past two years, Conservational International (CI) has been documenting the harmful effects of the DWF fleet and working with policymakers to identify solutions to these problems.

This 1-year Masters Project seeks to better understand mitigation strategies for DWF impacts in Liberia by exploring how modifying DWF access to Liberian waters could affect ecological and economic outcomes. Specifically, we combined economic, environmental, and social metrics in a framework to explore how altering inshore trawling activities by DWF vessels affects projected fish stock biomass and fishery-related income for Liberia. Using our bioeconomic framework, we estimate changes under several policy scenarios and ultimately conduct a cost-benefit analysis for each. Based on the quantitative and qualitative outcomes of our analyses, we provide policy recommendations to Conservation International and its partners in Liberia.

Bioeconomic Model Results

It was found that all scenarios which increase the access fee required of DWF's to fish in Liberia's EEZ observed a reduction in DWF fishing effort compared with the business as usual projection. In addition, each of these scenarios project increases in catch per unit effort of SSF throughout the time-horizon. It is important to note that equal preference was placed on the profits of the SSF fleet and revenue from DWF fleet in this analysis. If this value were to change, then the estimated net present value of benefits seen by NaFAA calculation would change (see discussion: Sensitivity Analysis).

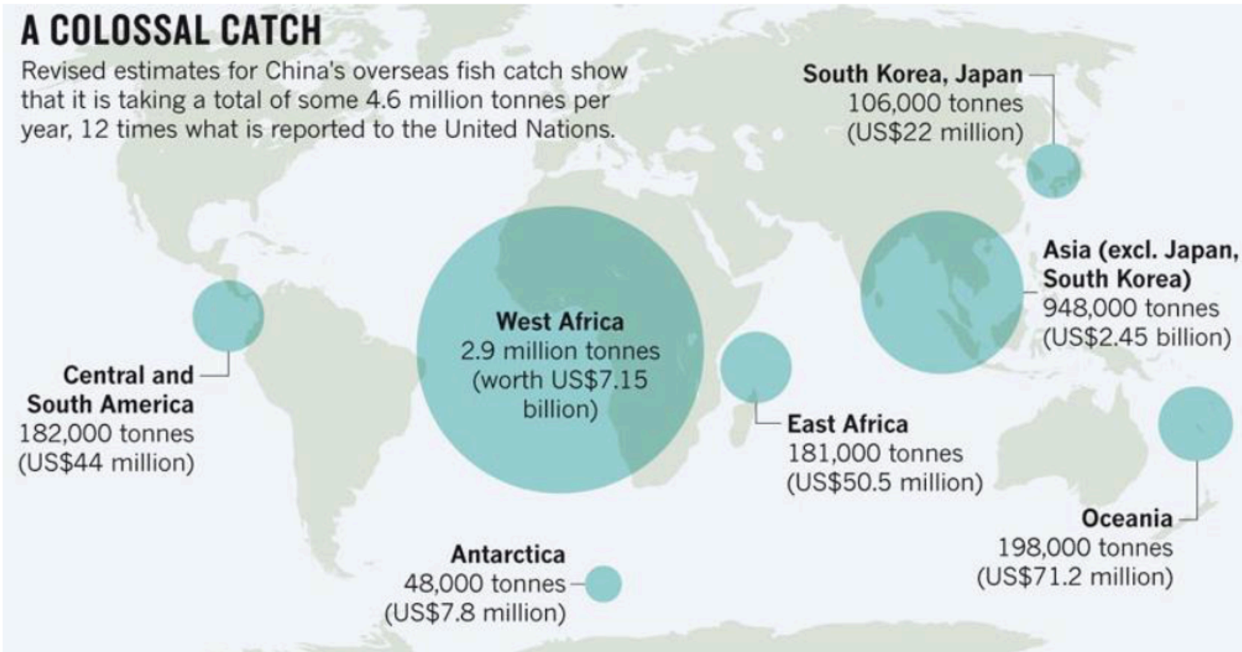
The metric used to assess health of the fishery was B/BMSY (Biomass over Biomass at maximum sustainable yield). While it was found under all scenarios that B/BMSY was estimated to be reduced from 1.21 to below 1, all scenarios considered which reduced DWF fleet effort saw an increase in final B/BMSY compared to the business as usual estimate. It is important to note that while the biomass changes from this analysis might not represent the real biomass changes in Liberia's fishery, the relative changes are expected to be accurate given the change in fishing effort by the DWF fleet under the various scenarios. In addition, if the SSF fishermen were to maintain their current effort satisfied with an increasing CPUE, the potential for stock recovery is high in Liberia's fishery.

Background and Project Significance

This project addresses the sustainability and equity of DWF in West Africa (Liberia). Based upon the previous work and ongoing priorities of Conservation International's DWF team, we provide a framework for economic analysis of countries allowing DWF vessels access to their EEZs to determine whether West African economies could benefit economically from limiting and/or adjusting DWF vessel access for trawlers. Financial analysis and modeling will provide a digestible and straightforward method of affecting policy change at a national and regional level and potentially garner increased local support to divest from any distant water fishing practice demonstrated to have outsized trade-offs. Through detailed research and literature review, Conservation International has already established several socio-economic negative externalities associated with these distant water access agreements. Environmentally, trawlers have been shown to contribute to seafloor degradation, turbidity, bycatch, and overfishing. Furthermore, this work's significance is underscored by the human rights issues Conservation International works to address in the global distant water industry as a whole. Through Conservation International's existing relationships, this research will be put directly into the hands of decision-makers, such as the National Fisheries and Aquaculture Authority. It will also be shared with local communities and civil society groups who have the potential to affect change through advocacy and collective action. CI-Liberia has close relationships with the Liberian government, the University of Liberia, and communities and civil society across the country, which will facilitate the broader positive impacts of this research project.

The Significance of Distant Water Fishing

Distant Water Fishing fleets play a significant role in global fisheries, particularly in the waters of developing coastal states, where economic and regulatory vulnerabilities enable exploitation. China and Taiwan alone account for nearly 60% of global DWF activity, with Japan, South Korea, and Spain each representing about 10% (UN, 2024). These fleets, particularly those operating in Africa's Atlantic coastal waters, have a documented history of non-compliance with local regulations, contributing to severe environmental and socioeconomic consequences, such as human rights issues and illegal, unreported, and unregulated fishing (IUU) (UN, 2024). Access agreements between foreign fleets and coastal nations are often negotiated based on financial and political considerations rather than scientific assessments of sustainable catch limits, leading to overfishing and resource depletion (Gutierrez & Lemma, 2024). Research suggests that between 7.7 and 14.1 million metric tons of fish, worth an estimated $8.9 to $17.2 billion, are illicitly traded each year, with Asia, Africa, and South America bearing the greatest economic losses (Figure 1). Despite the scale of these operations, compensation paid by foreign fleets is a fraction of the value they extract. China, for example, pays only 4% of the actual landed value of its catch in some agreements (UN, 2024). The failure to reinvest these revenues into local fisheries management, enforcement, or community development further exacerbates economic inequalities and weakens coastal states' ability to regulate their waters. As global fish stocks decline, 90% of commercially exploited stocks are already fished at or beyond sustainable limits, and DWF fleets are increasingly incentivized to expand their reach, further threatening food security and marine biodiversity in vulnerable regions (Gutierrez & Lemma, 2024). Without stronger governance frameworks and greater accountability for the actions of DWF fleets, the exploitation of developing nations' fisheries will continue to undermine both economic stability and long-term ocean health.



Source: PEW Charitable Trusts (April, 2013) "China's Foreign Fishing is Largely Unreported."[7]

Figure 1: Estimates of China's Distant Water Fishing Fleet

Small-Scale Fishing in Liberia

Liberian small-scale fisheries (SSF) are essential to the country's economy and livelihoods, employing about 33,000 individuals, with women making up 60% of the workforce (Jueseah et al., 2020). With 80% of participants being Liberian nationals and the remaining workforce comprising migrant labor from neighboring countries like Ghana, Togo, Senegal, and the Ivory Coast, this sector sustains the livelihoods of over 10,800 full-time fishers and 22,100 local and foreign fish processors and traders, directly supporting around 300,000 people in total (Jueseah et al., 2020; World Bank Group, 2021). The SSF fleet primarily targets fish for the domestic market, with the Kru and Fanti fisheries forming its backbone. Kru fishers, now operating over 3,800 canoes, are Liberian nationals that predominantly target demersal species such as cassava fish, groupers, and crustaceans. In contrast, Fanti fishers, largely migrants from Ghana, focus on small pelagic species like *Sardinella*, locally known as bonny, using ring nets (Conservation International, 2023). While the Fanti boats have seen limited growth due to raw material constraints, they still contributed around 63% of SSF catch from 2013 to 2020, a significant portion of which ensured local food security despite challenges like poor post-harvest handling (Jueseah, 2021).

Women are pivotal in Liberia's small-scale fisheries as traders, processors, and financiers. Among them, fishermen's wives are central figures, purchasing approximately 85-90% of the fish traded regardless of the season (Jueseah et al, 2020). They smoke and process fish, primarily *Sardinella*, which they sell to artisanal fish traders through market-based interactions. In addition to processing, these women provide informal, interest-free loans to fishers, covering essential fishing inputs such as boats and nets and family expenses like school fees, food, and medical care (Jueseah, 2021). In exchange, fishers repay with fish at prices up to 10% lower than market rates, ensuring a steady supply at favorable terms to them. The importance of these informal credits is underscored during the rainy season when adverse weather restricts fishing, and wives often assume the primary role of supporting household needs. One fisher's wife noted, "We are the men during the rainy season, providing all the domestic needs for the family" (Jueseah et al, 2020).

Fleet demographics and licensing

For a fee, DWF fleets can gain access to Liberian waters. Three main groups make up Liberian DWF fleets: the EU, China, and private. EU vessels from France and Spain once made up the largest fleets and focused on purse seine and longline fishing. They had access under the Sustainable Fisheries Partnership Agreement (SFPA), a tuna fishing access agreement between Liberia and the EU that allowed EU vessels access to Liberia's EEZ while simultaneously focusing on environmental sustainability, local growth, human rights, and shared accountability between the host and fishing states (European Commission 2024). However, Liberia received a yellow card from the EU because of its lack of effort in combating IUU, and the EU fleet pulled out of Liberia's EEZ. Since then, the EU fleet has been incompletely replaced by private vessels. The coastal trawl fleets from China have licenses for using both bottom and mid-water trawls, targeting coastal demersal and pelagic species and crustaceans. Chinese fleets are charged a flat rate of 10% of the landed value of their annual catch. The private fleets, under private access arrangements and include vessels flagged to Spain, France, Ghana, Senegal, and Belize, among others, target mostly tuna. These vessels can continue to operate in Liberia despite the yellow card because they are under private access agreements rather than the lapsed SFPA (Conservation International, 2023).

As stated before, Liberian national fleets are made of small-scale vessels. These are comprised of traditional Kru canoes 5-7 m in length, typically powered by sails and paddles, as well as large open wooden Fanti boats 10-15m long powered by up to 15 horsepower outboard or inboard engines, and semi-industrial fleets, which comprise of larger canoes powered by 16-200 horsepower engines (Jueseah et al, 2020). They both target small pelagics, demersal finfish, and crustaceans and enjoy exclusive fishing rights to the 6-mile Inland Exclusion Zone (IEZ), defined as all coastal waters within 6 miles of Liberia's coast. The IEZ was implemented in 2010.

Conflicts between foreign and national vessels

Industrial trawlers, predominantly Chinese-owned, further complicate fisheries management. Operating outside the 6 nautical mile zone, these trawlers target demersal and pelagic species, with bycatch rates reaching an alarming 70% (Conservation International, 2023). This practice raises concerns about resource sustainability and competition with SSF, mainly because juvenile species targeted by SSF are often discarded. While the trawl fleet has decreased in size since 2010, its impact on fish stocks remains a significant issue for resource managers (see Figure 3 in the appendix). Currently, six Chinese industrial trawlers operate in the region, with gross registered tonnage (GRT) ranging from 91 to 251 (Conservation International, 2023). These vessels typically have an average crew size of 17, though the exact composition varies significantly (Togba, n.d). Due to data limitations, detailed demographic information about the crew is difficult to obtain. While a small number of Liberian nationals may be part of these crews, their presence is negligible compared to the workforce employed in the small-scale fisheries sector.

The creation of the IEZ, preventing industrial fishing vessels from accessing the 6 miles closest to the coast, has created tension between the foreign DWF trawlers and national vessels. Previously, trawlers could bottom trawl along the coast and dominate the crustacean fishery. However, Liberia has a very short continental shelf, only 22 miles wide (Conservation International, 2023). Thus, trawlers were required to retreat from their original fishing zone, and their target species was consequently changed to demersal finfish. This created a spatial and economic concern. Despite being moved 6 miles offshore, the DWF trawlers compete for mobile fish stocks because the trawlers fish on the boundary line. Liberian fishers have reported that "coastal trawlers usually abandon destroyed fishing nets on our fishing grounds, catch all the fish, leave nothing for the locals, and pollute the ocean with unwanted catch" (Conservation International, 2023). Additionally, SSFs claim DWF trawlers are violating the IEZ and fishing within the boundaries at night (Conservation International, 2023). These concerns align with Jueseah et. al's (*forthcoming*) findings that the IEZ alone did not accomplish its goal of protecting SSF from DWF trawling pressure and that even after the implementation of IEZ, DWF catch increased while SSF catch continued to decrease (Figure 4). Their work also highlights the need for additional policy mechanisms to be explored that might complement the IEZ.

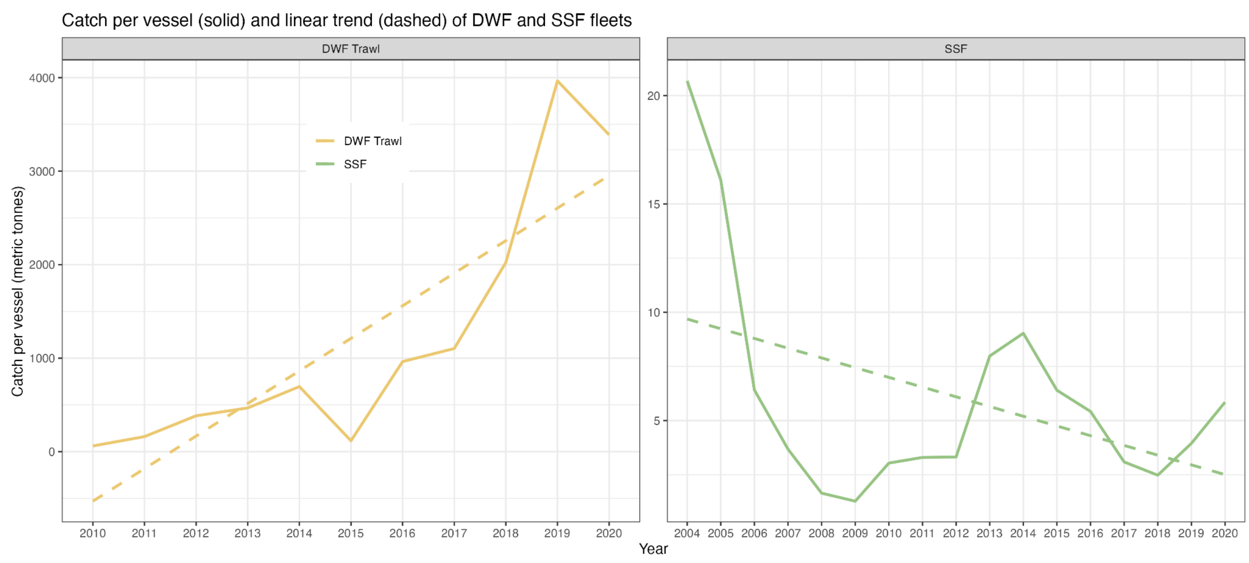


Figure 4: Catch per vessel and linear trend of DWR and SSF fleets

Social implications of DWF fleets

Overall, SSF represents 86% of the country's fishing industry (Wuor & Mabon, 2022). However, concerns regarding DWF fleets extend beyond the economy. Liberia's Global Hunger Index

(GHI) score for 2024 is 31.9. GHI scores range from 0 (best) to 100 (worst) and are calculated based on the percentage of undernourished people, underweight children, children with stunted growth, and child mortality rates (Global Hunger Index 2024). Liberia's score indicates serious food insecurity. While fish caught by SSF stays within local communities and is a crucial source of micronutrients for Liberians, the final destination of the fish landed by DWF trawlers is unknown, leading to a gap in necessary nutrients for coastal communities (Conservation International, 2023).

As a member of international organizations such as the United Nations (UN) and the African Union (AU), Liberia is a signatory to many different international protocols, including those under the International Labor Organization (ILO) and other AU protocols. These international declarations and protocols address gaps in local legal frameworks to ensure that global human rights standards are enforceable (Conservation International, 2023). In addition, Liberia has taken steps to provide its citizens with reasonable working conditions on DWF vessels, such as The Decent Work Act (Labor Law, 2015), which protects all workers in Liberia and "within the jurisdiction of the Republic." In addition, the Seaman Union in Liberia, as of 2019, was under a collective bargaining agreement (CBA) with six Chinese trawlers to ensure that Liberian fishermen were employed as part of the crew and paid according to their status (Conservation International, 2023). While Liberia has taken steps to minimize the socio-economic harm of DWF fleets, there are still considerable gaps in addressing work in fisheries, as they are primarily offshore. Primarily, key conventions of the ILO have yet to be ratified, such as C188, which establishes rules for employment on commercial fishing boats and prevents severe human rights violations, and C158, which protects employees against unfair termination of employment, including due to union membership and whistleblowing. In addition, key regulatory agencies share the power of authority in regulating the fisheries sector, which reduces their abilities to enforce regulations/laws/penalties, which may contribute to increased violations by foreign fleets.

Addressing the intersections

Liberia currently faces the daunting task of balancing the economic needs of its National Fisheries and Aquaculture Authority (NaFAA) and the social and environmental impacts of DWF fleets. NaFAA was established by an act of the national legislature in 2017 as an autonomous agency that was given the authority to manage the fisheries of Liberia (FAO, 2022). As an autonomous agency, NaFAA operates as a business entity, aiming to attract investment and generate adequate revenue to sustain its operations and manage and develop the fisheries sector. As a result, licensing fees to DWF fleets are its primary revenue source, indicating a large incentive to maintain DWF fleet operations within its EEZ. However, through the West Africa Regional Fisheries Project (WARFP - Liberia), NaFAA is additionally charged with developing the fishery to enhance social and economic gains (Prince, Berengere P. C, 2018). One implementation that NaFAA has already taken to address this is the establishment of the Inshore Exclusion Zone (IEZ) to ensure that industrial vessels were not interacting directly with fish stocks that artisanal fishers were targeting. This improved conditions and increased landings for Liberian artisanal fishers from 2011-2015, but continued to decline in the years after (Figure 4) (Prince, Berengere P. C, 2018; Jueseah et. al, *forthcoming*). Yet IUU fishing likely persists; this is inferred from the fact that Chinese DWF fleets have reported financial losses rather than profits from operating in Liberia yet continue to license their vessels and operate within the EEZ. However, Chinese distant water fishing is highly subsidized and may incentivize fleets to continue to fish even in unprofitable conditions (Wang, 2023). In addition, artisanal fishermen have reported deleterious interactions between themselves and foreign trawling fleets (Conservation International, 2023). These points illustrate the significance of identifying methods to simultaneously improve governance of Liberian fisheries while supporting the revenue streams of NaFAA as well as its artisanal fishers and coastal communities and mitigate both IUU fishing and human rights violations that have been prevalent in DWF operations in recent years.

Data Sources

Data used in this analysis were obtained both from primary reports obtained from NaFAA as well as publicly available data accessed online. Direct report data was provided by NaFAA in the form of six-years (2018-2023) of species-specific catch data for both SSF and DWF fleets, as well as a report on the estimated costs of fishing for the SSF fleet. Publicly available data was obtained through the “Report of the FAO/CECAF Working Group on the Assessment of Small Pelagic Fish”, which included catch, effort, and catch per unit effort estimates for *Sardinella spp.* in Liberia, for both SSF and DWF fleets from 1990 to 2017 (FAO, 2019). Used length-based data and other studies to estimate biomass in each zone for different age-classes (Yokie, A. 2019).

Methods and Technical Approach

We address our key objectives using a 3-pronged approach:

1. **Bioeconomic Optimization:** The first step in our approach combines biological and economic components to model the decision-making behaviors of both DWF and SSF fleets within the sardine fishery in Liberia. The model is manipulated through different scenario inputs to calculate the optimal access fee NaFAA should charge to DWF fleets to maximize the economic benefits to SSF fleets as well as maintain their economic benefits via revenue gained from charging the access fee. The optimization was conducted using the `nloptr` function from the `nloptr` package (Johnson, S., N.D.).
2. **Non-Market Valuation:** Non-market evaluations were estimated through a combination of literature review, data analysis, and calculations. Final estimations were determined by integrating outputs from our bioeconomic model.
3. **Qualitative Analysis:** For non-market evaluations where monetary estimates were difficult to determine due to complexity, data limitations, or time constraints, we conducted comprehensive literature reviews. This approach provided valuable qualitative insights to support our analysis.

Bioeconomic Model

a. Biological Model

Our biological model focuses on *Sardinella spp.,* encompassing both *Sardinella aurita* and *Sardinella maderensis*. *Sardinella spp.* is caught in the largest amount and considered to be most important by local fishermen (Yokie, A. A., 2019). As our analysis is centered around addressing the impacts of DWF activity on SSF catch, this finding was an important factor in our decision of species. Both of these species share similar life-history traits with population demographic parameter estimates completed, and tend to be found together in Northwest African coastal waters (Yokie, A. A., 2019; Balde et al., 2019). Finally, *Sardinella spp.* carrynig capacity K and an estimate of total biomass for the FAO-defined Northern Stock were available from the FAO (FAO, 2019). While a multi-species approach is possible and would likely provide additional insight to NaFAA, our timeline and available resources limited our analysis to one species. We intend the provision of our current model to be conducive to further analysis such as including additional species as NaFAA desires.

When constructing the biological model, we employed an adapted version of Mcich et al.'s spatially age-distributed model to reflect the apportionment of Liberia's coastal fishing effort into three zones: the EEZ (zone 1), IEZ (zone 2), and nearshore (zone 3), with an additional term for more accurate biomass growth estimates (Mcich et al., 2017; Seijo et al. 1998; Schaefer, 1954). Similarly, the population structure of *Sardinella aurita* has been described in Northwest Africa as following a cross-shore population structure, with juveniles primarily occupying an area closer to shore, and adults moving further offshore (Conand, 1977). Given the similarities between *S. aurita* and *S. maderensis*, we make the assumption that both species follow a similar spatial age distribution, and as such catch patterns in one zone of the fishery might affect different age classes within the population, and different actors within the fishery. The spatially age distributed model we employ assumes two primary age groups of *Sardinella* spp., with the juvenile age group contributing to the recruitment potential of the population, and the adult age group contributing to the spawning potential of the population.

Given the zoning of the fishery, the adult age group is divided into two functional populations, in which the first population experiences fishing pressure from DWF and SSF willing to travel outside of the IEZ to fish, and the second population experiences fishing pressure from SSF fishing within the IEZ. The third (juvenile) population experiences fishing pressure from SSF fishing nearshore. It is assumed that fish biomass is distributed evenly within each zone as well as fishing effort. This reflects the contextual knowledge of fishermen within a fishery in directing their effort towards known schooling locations. In addition, it accounts for the relative change in catch per unit effort of one fleet dependent on the behavior of a competing fleet. Finally, this model structure allows for additional terms to be included which reflect either the migration of fish between zones or the migration of fishermen between zones. The biological model is structured as follows:

Biological Parameters and Formulas

$\gamma =$ Annual production of juveniles as proportion of adult stock biomass (tonnes)

$\mu =$ Zone natural mortality rate (year^{-1})

$q_f =$ Catchability coefficient for fleet f (effort days^{-1})

$v =$ Proportion of juvenile biomass that recruits each year (year^{-1})

$\chi =$ Proportion of recruited biomass entering Zones 1 or 2

$r =$ Intrinsic rate of population increase (year^{-1})

$K =$ Population carrying capacity (tonnes)

$$(1)\ B_{t,1} = vB_{t-1,j}(1-\chi) - \mu B_{t-1,1} - q_{SSF}B_{t-1,1}e_{t-1,1} - q_{DWF}B_{t-1,1}E_{t-1}$$

$$(2)\ B_{t,2} = vB_{t-1,j}\chi - \mu B_{t-1,2} - q_{SSF}B_{t-1,2}e_{t-1,2}$$

$$(3)\ B_{t,j} = \gamma_{t-1} - vB_{t-1,j} - \mu B_{t-1,j} - q_{SSF}B_{t-1,j}e_{t-1,j}$$

$$(4)\ \gamma_t = r(B_{t,1} + B_{t,2})(1 - \frac{B_{t,1} + B_{t,2}}{K})$$

Where equation 1 represents the adult *Sardinella spp.* biomass in zone 1. The biomass in zone 1 for a given year is a function of the recruitment of juveniles from the year prior, less the natural mortality of fish and fishing mortality by SSF and DWF fleets. The proportion of juveniles recruited to the adult population is determined by v, which represents a proportion of juvenile biomass. It is assumed that all juveniles surviving in a given year matriculate into the adult age class the following year. The incorporation of the $(1-\chi)$ term reflects differential recruitment to each zone. It is assumed that equal amounts of juveniles recruit to either zone in this model, although may be changed given contextual knowledge of *Sardinella spp.* distribution in Liberia's waters, and the knowledge that fish must pass through zone 2 prior to entering zone 1. Natural mortality is incorporated through μ, which represents the proportion of adult biomass in zone 1 which dies due to natural causes each year, independent of density. Due to high variability in natural mortality estimates for *Sardinella spp.* in Liberia, it was estimated by using average values listed in Baldé et al., 2019 (2), Appendix table 1. We assumed constant natural mortality rates across age classes and through time. Fishing mortality in zone 1 is incorporated through two terms, which are the product of the catchability coefficient for *Sardinella spp.* for each fleet q_f, the biomass in zone 1, and effort by each fleet in zone 1. The catchability coefficient for each fleet was estimated using the `bsm` function from Chris Free's `datalimited2` package in R (Free, C.M., 2018; Froese et al., 2017). This requires data with year, catch, and at least five years of CPUE data. The catch data were obtained from the "Report of the FAO/CECAF Working

Group on the Assessment of Small Pelagic Fish" (FAO, 2019). As the units for effort in this report were unclear, effort data was obtained from Rousseau et al., 2024, which included a database of mapped global effort for Liberia from 1950-2017 (Rousseau et al., 2024). These data were filtered to the years after 2003, to account for potential uncertainty due to the Liberian civil war. We then combined the catch and effort data, and aggregated across fleets to calculate the catch per unit effort each year. This allowed us an estimate for a range of catchability values. We used the range to pick an initial value and parameterize the value for the SSF fleet. We then assumed that twice this value would account for the increased efficiency of the DWF fleet.

Equation 2 represents the adult *Sardinella spp.* biomass in zone 2. The biomass in zone 2 for a given year is a function of the same processes that determine biomass in zone 1, with the exceptions that SSF effort in zone 2 is independent of effort in zone 1, and that there is no fishing mortality caused by DWF, as they are only allowed to fish in zone 1 (outside of the IEZ). That is, biomass in zone 2 is a function of the proportion of juvenile biomass recruited to zone 2, less the natural and fishing mortality of adult fish in zone 2.

Equations 3 and 4 represent the juvenile *Sardinella spp.* biomass in zone 3 each year. The juvenile biomass in each year is a function of adult spawning (equation 4) less recruitment of juveniles into the adult age class, natural and fishing mortality. Spawning is incorporated via a modification of the Schaefer surplus production model, where adult biomass in the year prior contributes to juvenile biomass in the following year, and is a function of the intrinsic rate of population increase r and population carrying capacity K (Schaefer, 1954). The parameters r and K were obtained through the `bsm` function, and referenced to values reported in the "Report of the FAO/CECAF Working Group on the Assessment of Small Pelagic Fish" (FAO, 2019; Free, C.M., 2018; Froese et al., 2017). The use of adult biomass reflects the importance of harvesting adult fish as opposed to juvenile fish due to their increased fecundity, but that juveniles may contribute significantly to harvest depending on fishery health and dynamics. Natural and fishing mortality in zone 3 follow the same processes as in zones 1 and 2, with the exception that effort in zones 2 and 3 are independent of one another.

b. Economic Model

The economic model seeks to solve a dynamic optimization problem where NaFAA chooses the optimal access fee, alpha, charged to distant water fleets in order to maximize their own revenue needs while also prioritizing the needs of small-scale fishers. The equations for the economic model are as follows:

Economic Parameters and Formulas

$\phi = \text{Rate of reinvesting in fisheries (effort days USD}^{-1}\text{)}$

$p = \text{Fish price (USD ton}^{-1}\text{)}$

c_z = Cost for SSF effort in zone z (USD effort days^{-1})
c = Cost for DWF effort (USD effort days^{-1})
α = Fee (% of landed value)
β = Equity weighting parameter (no units)

(5) $e_{t,1} = e_{t-1,1} + \phi[-(c_1 e_{t-1,1})^2 + pq_{SSF} B_{t-1,1} e_{t-1,1}]$

(6) $e_{t,2} = e_{t-1,2} + \phi[-(c_2 e_{t-1,2})^2 + pq_{SSF} B_{t-1,2} e_{t-1,2}]$

(7) $e_{t,3} = e_{t-1,3} + \phi[-(c_3 e_{t-1,3})^2 + pq_{SSF} B_{t-1,3} e_{t-1,3}]$

(8) $E_t = E_{t-1} + \phi[-(cE_{t-1})^2 + (1-\alpha) pq_{DWF} B_{t-1,1} E_{t-1}]$

(9) $\mathrm{C_{t,SSF,z}} = q_{SSF} B_{t,z} e_{t,z}$

(10) $\mathrm{C_{t,DWF}} = q_{DWF} B_{t,1} E_t$

(11) $\Pi_{t,SSF} = \sum_{z=1}^{z=3} pC_{t,SSF,z} - c_z e_{t,z}$

(12) $\mathrm{NPV} = \sum_{t=1}^{t=T} \rho^t [\beta \Pi_{\mathrm{t,SSF}} + (1-\beta)\alpha \mathrm{pC_{t,DWF}}]$

Where equation 5 represents SSF effort in zone 1 for a given year. SSF effort in zone 1 is a function of the previous year's effort and the net return of effort multiplied by the rate of reinvestment in fisheries ϕ (Smith, 1969). Net return for a given year is calculated by subtracting gross costs from gross profits. Gross profits are calculated by multiplying the market price of *Sardinella spp.* p by the catchability coefficient for the SSF fleet q_{SSF}, biomass in zone 1 $B_{t,1}$, and the SSF effort in zone 1 $e_{t,1}$. Gross costs are calculated by multiplying the SSF effort in zone 1 by the cost per unit effort in zone 1 c_1, and squaring the term to ensure convexity during optimization. Therefore, if the net return for SSF effort in zone 1 is negative, effort will decrease in the following year. The magnitude of this change is determined by multiplying the net return by ϕ, and so reflects both a fleet's need to fish as well as their ability to adapt to fishery health. Equations 6 and 7 reflect the same decision-making process for SSF effort in zone 2 and 3. These functions differ from equation 5 in that the cost of fishing effort in either zone, biomass, and effort differ from zone 1. The market price of *Sardinella spp.* was pulled from previous literature (Jueseah et al., 2020). In this model, we assume that the market price captures the true value of *Sardinella spp.*, even though many fishers eat a portion or all of their catch. Costs per unit effort for SSF fleet effort were derived using NaFAA's report on estimated costs of fishing, as well as backing out their costs using SSF incomes as estimated by Saye (2024) and scaled for the proportion of SSF catch that is *Sardinella spp*. Only boat captain incomes were considered in the cost calculation to reflect their decision making-making authority. Our estimate for the rate of reinvestment in fisheries was obtained from Mcich et al., 2017, and parameterized to represent the robustness of effort to net returns by SSF in Liberia.

Equation 8 represents DWF effort for a given year. It reflects the same decision-making process that SSF fleets follow, with the exception that α is included in calculating their gross profits. This reflects the fee that NaFAA charges DWF fleets, which influences their net return, and as such provides a mechanism by which NaFAA can modulate their behavior. The Cost per unit effort for DWF was backed out using total cost values estimated by Virdin et al. (2022) and scaled for the proportion of DWF catch that is *Sardinella spp*.

Equations 9 and 10 represent the harvest in a given year for SSF and DWF fleets, respectively. Both equations are a function of the fleet's catchability coefficient multiplied by the biomass available in their accessible zones and effort in a given year.

Equation 11 represents the net profit for the SSF fleet in a given year. It is a function of the sum across zones of the price of *Sardinella spp.* multiplied by the harvest for each zone (gross profit), less the cost per unit effort multiplied by the effort for each zone (gross costs). That is, the total SSF profit is the sum of their revenue from fish caught less their cost of fishing effort. We assume that both fleets are profit-maximizing when making decisions regarding harvest and effort. While we do not use a function for the net present value of the DWF fleet's economic benefits, it is implicitly calculated in their harvest function.

Finally, equation 12 represents the net present value of economic benefits for NaFAA. Their present value of benefits for each year are the sum of SSF profit and the revenue collected from the DWF via the access fee, which is derived by multiplying the value of DWF harvest by the access fee α. We employ the constant β as an equity weighting parameter for NaFAA's preference between both fleets' economic benefits. A higher β will place more importance on the small-scale fishers, and can be adjusted to reflect NaFAA's prioritization of the small-scale fishers. This term is then multiplied by the discount factor ρ^t to calculate the present value of future benefits of the projection in 2023 dollars. We used a discount rate of 0.05, but this can be modified according to NaFAA's needs. Finally, the present value of benefits are summed across years to obtain NaFAA's net present value of benefits.

Estimates for the starting biomass and effort in each zone were obtained using R. A viable total biomass value for 2023 was estimated by comparing the value from the `bsm` function output referenced to the biomass as of 2018 reported in the "Report of the FAO/CECAF Working Group on the Assessment of Small Pelagic Fish" (FAO, 2019; Free, C.M., 2018; Froese et al., 2017). The total biomass value was then separated between adult and juvenile biomass through estimates of LBSPR for *Sardinella maderensis* in Liberia (Yokie, A. A., 2019). With the assumption that adult biomass was distributed approximately evenly between zones 1 and 2, initial biomass estimates for each zone were obtained. Total effort for both the SSF and DWF fleets were obtained from Rousseau et al., 2024, and apportioned between zones assuming that

SSF effort would be highest in the closest zone which contained adult fish, lower further from shore, and lowest directed towards juveniles due to undesirable nature of catching juvenile fish (Rousseau et al., 2024; Yokie, A. A., 2019). Finally, with reasonable initial estimates for biomass and effort in each zone, these were fed into the model with our parameter values (Table 4) and calibrated using the `optim2` function from the `calibrar` package and a custom function adapted from the `negLL` function from the `MQMF` package (Haddon, M., 2021; Oliveros–Ramos, Shin, 2025). This custom function employs maximum likelihood methods to calibrate initial state guesses against the observed catch data that NaFAA provided. A description of the general process behind maximum likelihood methods can be found in Malcolm Haddon's "Using R for Modelling and Quantitative Methods in Fisheries" (Haddon, M., 2021). Initial state values used can be found in Table 5.

Non-market and Qualitative Methods

The non-market evaluation and qualitative sections of the report aim to add additional context to the state of the Liberian fisheries through costs and benefits that are not encompassed by the bioeconomic model. The first step in this process was to conduct a thorough literature review of categories impacting Liberia's fisheries. When possible, these impacts were transformed into a value in units of USD. Values were calculated using the outputs from the bioeconomic model and evaluated under each scenario: business as usual, optimal, and ban. Impact categories that did not have enough available information to produce a value in USD underwent a qualitative analysis. The qualitative analysis included an explanation of each the current impact under business as usual, what is being done to combat the impact, and if possible how the impacts may change under the optimal and ban scenarios.

The USD quantified impacts estimate the financial burden of maintaining the current 'business as usual' (BAU) approach in Liberia. These costs and benefits often go unnoticed because they are not typically expressed in dollar amounts. To address this, the methodology relies on existing literature to assess the scale of impact for each indicator and then applies market-based valuations to approximate the theoretical financial costs. The calculations reflect the cost of six industrial trawlers operating under BAU conditions, with a counterfactual scenario in which no trawlers operate within Liberia's EEZ. This counterfactual does not account for potential changes in the operations or behavior of artisanal fishers. While it is likely that removing foreign trawlers would create a vacuum that would be filled in some capacity, such secondary effects fall outside the scope of this analysis.

We are using literature and past research to estimate stock decline. A study in Liberia reported catch data in 2006, 2007, and 2016, giving an average rate of decline over this time of 818 tons/year (818,000 kg/year) for our business as usual case (Jueseah, 2021). With the estimated biomass decline, the next step is to multiply the decline by the market prices of the sardines to find the loss of economic value to small-scale fishers. An academic paper provides data on local market prices, giving us 1.3$ USD/kg (Jueseah *et al*., 2020). We then use the change in B/MSY from our model to estimate the change in annual biomass loss attributable to our changes in our policy scenarios. Therefore:

X kg/year x 1.3 USD = USD/year in sardine biomass lost to local markets in BAU.

Quantifying juvenile bycatch is done by analyzing the value of lost potential adult catch. While there are no Liberia-specific studies on bycatch, a study conducted off Mauritania observed 1400 trawls (for fisheries specifically targeting *Sardinella*) between 2001 and 2005 (Zeeburg and De Graff, 2006). The findings showed that bycatch was "considerable" especially during high periods of abundance during summer. Another global analysis found bycatch values from different regions, and with the inclusion of 13 specific countries, gives a 70% bycatch rate for Africa. This number is skewed by larger countries (specifically South Africa). Still, the authors also state it is likely an underestimate - therefore, we accept this 70% value as transferable for Liberia's industrial fleet (Davies et al., 2009). An Environmental Justice Foundation report found that 44.6% of bycatch by weight in Ghana was juvenile (Environmental Justice Foundation, 2020). By transferring the findings of these two studies, we quantify the juvenile bycatch in Liberia. This calculation also assumes that some market value is being derived from these juvenile sardines as opposed to them being completely discarded. The lost economic opportunity of these juveniles is calculated using standard market price. We then multiple the juvenile tons of sardines by a growth factor derived from our model (4.51x). Finally, we subtract the actual bycatch tonnage, from the hypothetical tonnage of fully grown sardines. This produced the following equation:

Tons of DWF catch x bycatch x juvenile % = juvenile bycatch
(Juvenile bycatch x growth factor) - juvenile bycatch = loss market value

Quantifying trawler fuel emissions is done using a study that gives the average fuel consumption and carbon emissions associated with fish capture using industrial trawlers. According to the findings, capturing one metric ton (MT) of fish consumes, on average, 1,722 liters of fuel, resulting in 4.65 kilograms (kg) of CO_2 emissions per kg of fish landed (Parker and Tyedmers, 2015). NaFAA industrial catch data gives BAU DWF landings of 1,387,870 kg/yr. Next, the social cost of carbon (SCC) was applied to assess the economic impact of these emissions. The global SCC was adjusted to reflect Liberia's share of the global population, assuming the total global population is 8,086,437,900 and Liberia's population is 5,493,031. Liberia's population represents approximately 0.06795% of the global population, and when applied to the global SCC value of $185 per metric ton of CO_2 we get a "Liberian SCC" of approximately $0.13 per ton of CO_2 (Carleton et al., 2020; US Census Data, 2024).

CO_2/kg landed x kg landed/yr x 0.00110231 (kg to tons conversion) = tons of CO2
Tons of CO2 x 0.13 = cost in SCC for Liberian Citizens

Table 1: Final list of the impact categories, and the resulting method for evaluation based on available data and literature. *See appendix, Figure 12 for each scenario's calculations*

Impact Categories Evaluated	**Analysis**
Biomass Loss	Quantitative

Juvenile Bycatch	Quantitative
Social Cost of Carbon	Quantitative
Small Scale Fishing Income	Qualitative
Small Scale Fishermen Risk	Qualitative
Fish Processor Health	Qualitative

Results

1. Table of Results

Table 2: Final results illustrating model outputs, nonmarket and other industry valuations under three different policy scenarios. All values are in 2023 USD. N/A values represent no way to calculate change for given scenarios.

Category	Indicator	Business as Usual	Scenario 1 (50% Access Fee)	Scenario 2 (100% Access Fee)	Scenario 3 (Ban)
Model Results	Value ($) attributed to SSF	$913,470	$914,287	$915,273	$926,229
	Value ($) attributed to NaFAA	$486,210	$597,352	$720,837	$472,079
	Model Total	$1,399,680	$1,511,639	$1,636,110	$1,398,308
Ecosystem Impacts	Biomass Loss	- $1,063,400	-$1,052,766	- $1,031,498	-$ 893,256
	Social Cost of Carbon	-$ 926	-$876	- $ 818	-$251
	Juvenile Bycatch	-$ 1,672	-$1584	- $ 1,479	-$ 454
Total		$333,682	$456,413	$602,315	$504,347

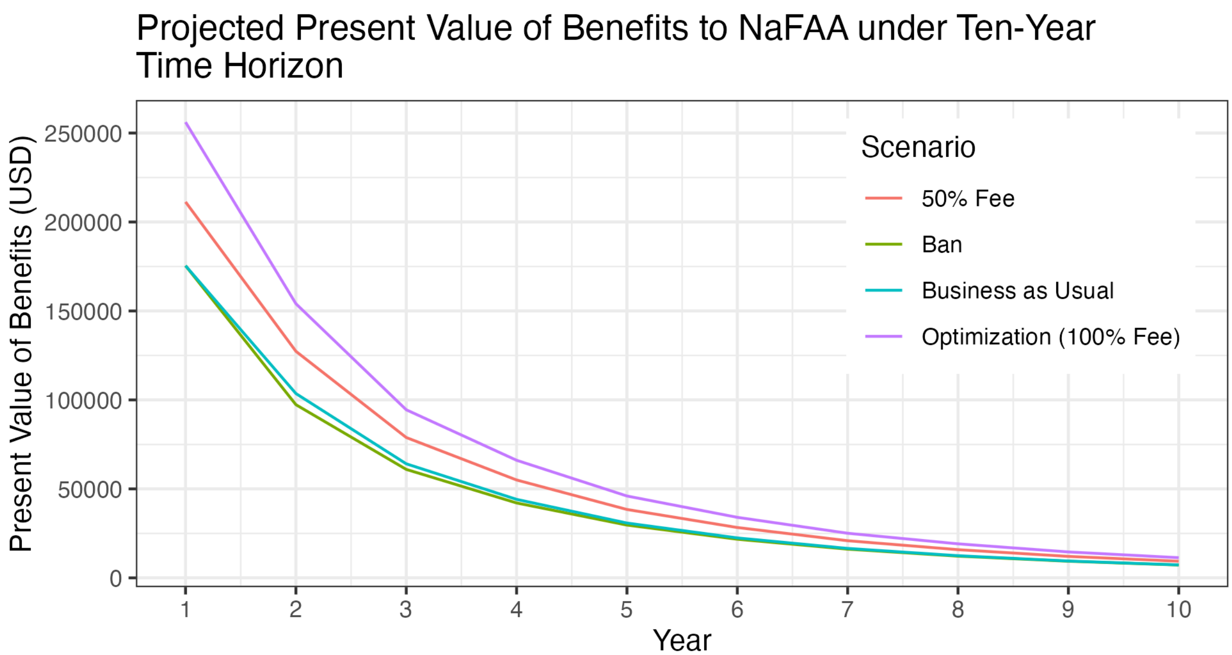


Figure 8: Projected present value of benefits to NaFAA under ten-year time horizon for each scenario.

Table 3: Model outputs for *Sardinella* biomass and harvest under three different policy scenarios.

Category	Indicator	Business as Usual	Scenario 1 (50% Access Fee)	Scenario 2 (100% Access Fee)	Scenario 3 (Ban)
Biomass	End B/BMSY	0.204	0.205	0.207	0.220
***Sardinella* Harvest**	DWF Harvest (tonnes)	1387.87	1315.14	1227.86	376.50
	SSF Harvest (tonnes)	2140.69	2142.94	2145.66	2175.23

Simulation of DWF dynamics under different access fees

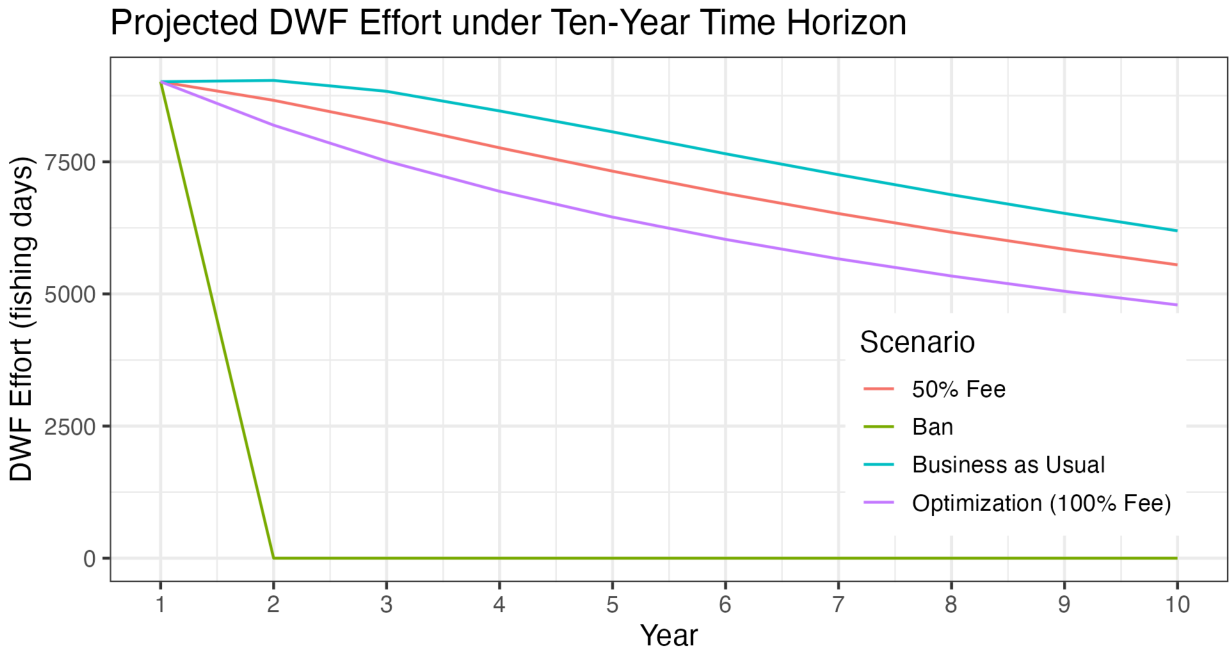


Figure 9: Projection of DWF effort under ten-year time horizon for each scenario.

Table 4: Parameter values used in the bioeconomic model. See Methods and Technical Approach for estimation of parameter values.

Parameter	Value	Parameter	Value
μ	0.43	c_1	0.060
χ	0.5	c_2	0.045
v	1	c_3	0.040
r	0.45	p	500
q_{DWF}	0.00000294	β	0.5
q_{SSF}	0.00000147	ϕ	0.005
c	0.045	δ	0.05

Table 5: Initial state values used in the bioeconomic model. See Methods and Technical Approach for estimation of initial state variables.

Initial State Variable	Value
$B_{i,1}$	14205
$B_{i,2}$	12480
$B_{i,3}$	6004
K	53855
$e_{i,1}$	15930
$e_{i,2}$	16827
$e_{i,3}$	7002
E_i	9015

Five-Year Time Horizon

When running the model under initial parameter values and calibrated initial state values, over 5 years, with NaFAA placing equal weight on the profit of small-scale fishers and the revenue from DWF, the optimal solution found was to raise the price of the access fee to 100%, leading to a net present value over 5 years of $616,737 USD, in 2023 dollar value. This solution would cause a decline in effort from DWF due to net losses, and eventually lead them to leave the fishery due to net capital loss. Compared to the business-as-usual case, this would increase the net present value of fisheries revenues by $198,707. While the optimal solution represents an effective ban of DWF from Liberia's EEZ, if NaFAA were to immediately ban and restrict access by DWF, the net present value of fisheries revenues would decrease by $12,558 compared to the business-as-usual case. Increasing the access fee to 50% would lead to a net present value of benefits of $510,935, which is an increase of $92,905 from the business as usual case. This solution would cause a decline in fishing effort from DWF, but it is uncertain whether or when they would leave the fishery, it would bring in additional benefits without causing immediate exit of the fishery by the DWF fleet.

In each scenario, it can be seen that a reduction in effort by DWF leads to an increase in catch from the same level of effort by SSF fleets. While the magnitude of this increase in CPUE is marginal within the model, it implicates the effect that DWF harvesting *Sardinella spp.*, in Liberian coastal waters has on SSF. As both fleets are harvesting the same resource, the change in effort by one fleet will have an opposite effect on the catch per unit effort (CPUE) of the competing fleet. The true magnitude of this effect is difficult to quantify without additional information or observations within the fishery, but the overlap of *Sardinella spp.* distribution between fishing grounds indicates that the effect could be larger than the direct interaction between SSF and DWF catch patterns.

Ten-Year Time Horizon

When running the model under initial parameter values and calibrated initial state values, over a 10-year time horizon with NaFAA placing equal weight on the profit of small-scale fishers and the revenue from DWF, the optimal solution found was to raise the price of the access fee to 100% again, leading to a net present value over 10 years of $720,837 USD, in 2023 dollar value. This solution would cause a decline in effort from DWF, and similarly to the five-year time horizon, lead them to eventually leave the fishery. Compared to the business-as-usual case, this would increase the net present value of fisheries revenues by $234,627. If NaFAA were to immediately ban and restrict access by DWF, the net present value of fisheries revenues would decrease by $14,131 compared to business as usual. Increasing the access fee to 50% would lead to a net present value of benefits of $597,352, which is an increase of $111,143 from the business as usual case. This solution would cause a decline in fishing effort from DWF, and as with the five-year time horizon, while it is uncertain whether or when they would leave the fishery, it would bring in additional benefits without causing immediate exit of the fishery by the DWF fleet.

Similarly to the five year time horizon, both the optimal scenario and ban scenario cause a reduction in DWF fishing effort, which increases catch per unit effort of SSF throughout the projection. In this analysis, it is important to note that the weighting parameter (beta) was set to 0.5, indicating that NaFAA places equal importance on the profits of SSF and revenue from DWF. If this value were to change, then the NPV calculation would change (see discussion: Sensitivity Analysis).

The metric used to assess health of the fishery was B/BMSY (Biomass over Biomass at maximum sustainable yield). BMSY was obtained within the output of the `bsm` function run to estimate additional biological parameters (Free, C.M., 2018; Froese et al., 2017). While it was found under all scenarios that B/BMSY was estimated to be reduced from 1.21 to below 1, all scenarios considered which reduced DWF fleet effort saw an increase in final B/BMSY compared to the business as usual estimate. It is important to note that while the biomass changes from this analysis might not represent the real biomass changes in Liberia's fishery, the relative changes are expected to be accurate given the change in fishing effort by the DWF fleet under the various scenarios. In addition, if the SSF fishermen were to maintain their current effort satisfied with an increasing CPUE, the potential for stock recovery is high in Liberia's fishery.

2. Non Market Valuation : Ecosystem Health

Sardine biomass decline is an ecosystem impact caused by the increased fishing pressure of foreign trawlers operating within Liberia's EEZ. Sardines are an economically important species in Liberia and ecologically important as forage fish are a critical nutrient source for larger species (Pikitch et al., 2014). A 2018 report found that the region is in danger of sardine stock collapse due to overexploitation (FAO, 2019). Earlier research similarly found a decline in the greater North West African region's sardine stock from 1996-2006 (Porz et al., 2024). This decline tends to accelerate as the stock is pushed beyond optimal harvest rates. As exhibited in numerous fisheries worldwide, there is a tipping point where species collapse occurs (e.g., the Northern Pacific Sardine fishery saw a drastic 98% decline (2006 and 2020) and is considered collapsed (Stimson Center, 2024). While Liberia's sardine stock does not seem to beat such a tipping point, its growth and collapse dynamics underscore the importance of careful management for the target species. For this project, sardines have been chosen as a single species to analyze. They will inform the biological model and serve as a representation of the greater Liberian fishery. While a holistic assessment of multiple species would be ideal, the data limitations and the project's scope make this analysis the most viable and meaningful. The decision to select sardines primarily comes from their high importance as a local food source (Yokie, A. A., 2019). In addition, there are readily available catch data, estimated biological parameters, and stock assessments for *Sardinella* spp. previously completed in the region (FAO, 2019; Yokie, A. A., 2019). Using our specific methodology in valuing this impact category, we find an annual market loss of 1,063,400 USD in the BAU scenario. It is important to note that for this scenario we value the market impacts of sardine decline generally - which is due to many factors, and this number does not specifically embody the negative impact of the DWF trawlers. However, by comparing our scenarios, we see an improvement in this market loss, when DWF vessels are charged a higher access fee.

Bycatch is an ecosystem impact indicator caused by Liberia's DWF vessels, as trawling operations are known to lead to high levels of bycatch. Bycatch can be defined as "unintended, non-targeted organisms caught while fishing for particular species (or sizes of species)" (Zeeburg and De Graff, 2006). Instead, we considered that juvenile sardines caught in Liberia are bycatch since the main target is adult sardines. Therefore, we focused on quantifying and valuing sardine bycatch to maintain the single-species analysis from our biological model. Bycatch of juveniles poses an economic loss since juvenile sardines are being harvested at a net lower tonnage and likely lower value than if they had been allowed to grow to maturity. In 2010, Liberia established a 6-mile Inshore Exclusion Zone (IEZ) reserved for small-scale fisheries. To protect juvenile fish habitats, trawlers are prohibited from accessing these areas. While this is a priority for Liberian fishery management, bycatch remains a problem, and trawlers operate directly on top of this line, and the IEZ likely is not a comprehensive enough management to mitigate this impact (Basurto et al*.,* 2024). Using our methodology for this specific impact category, we find an annual market loss of 1,671.67 USD in the BAU scenario.

Trawler fuel consumption is an ecosystem impact indicator as a source of CO_2 emissions, manifesting as an environmental cost. Atmospheric CO_2 emissions' contribution to climate change comes at a global cost, measured and defined as the social cost of carbon (SCC). The SCC has been thoroughly researched and defined as a number that "theoretically captures all future net damages associated with a marginal increase in CO_2 emissions" (Wuor and Mabon, 2022). Though the number of vessels is small, they work at a consistent capacity. Even though emissions are negligible on the global scale of carbon, the SCC provides a framework for establishing the distributional costs of this contribution. Using our methodology for this specific category, we find an annual market loss of 924.83 USD in the BAU scenario.

3. Industry Valuation

a. Liberian Fisher Income

Economic activity within the SSF is seasonal, driven by weather and catch availability. During the dry season (October to April), favorable conditions yield high catches, yet infrastructure limitations for fish traders and processors lead to substantial post-harvest losses (Jueseah et al, 2020). Adverse weather curtails fishing during the rainy season (May to October), reducing operational days and catches. This seasonal shift in fishing activity results in an average of five fishing days per week during the dry season and only two days per week during the rainy months (Jueseah et al, 2020).

Other key buyers in the SSF value chain include Korean traders and artisanal fish traders, each with distinct operational dynamics. Korean traders purchase large volumes from Kru fishers, often exceeding 300 kilograms of fish daily. They transport their purchases using privately organized vehicles equipped with chillers for eventual export from Monrovia (Jueseah et al, 2020). Artisanal fish traders, also predominantly women (98%), operate on a smaller scale, buying on average 70 kg but up to 150 kg of fish per transaction and relying on public transport or foot to distribute the fish to local clients (Jueseah et al, 2020). Their interactions with fishers are market-driven, with no long-term credit arrangements. Local consumers represent the smallest market segment, purchasing only 2-10% of the total fish, typically bonny, traded during the dry and rainy seasons (Jueseah, 2020). See Figures 4 and 5 for the value chain from each fishery.

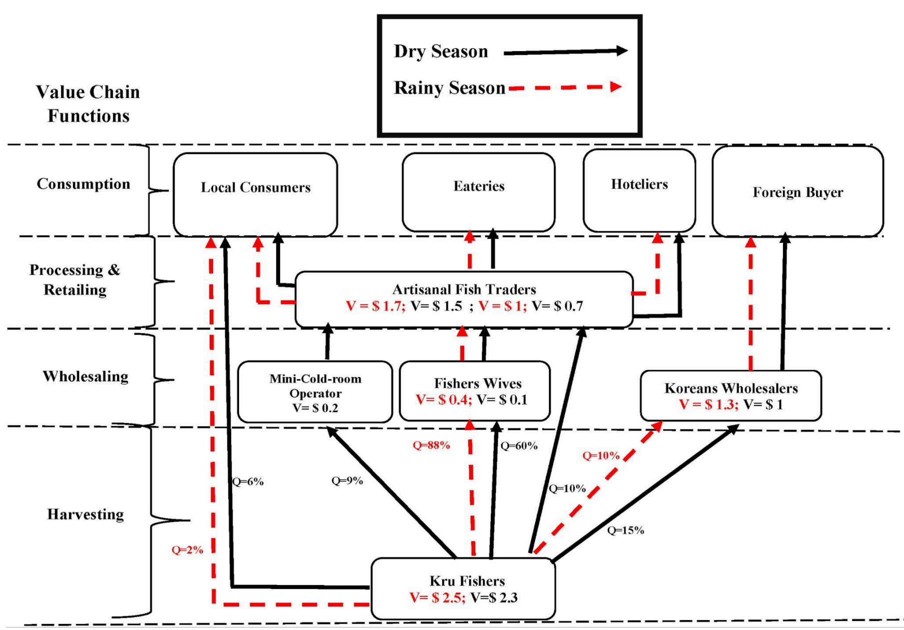


Figure 2: Kru fishers value chain for shares (%) of cassava fish traded and value-added by each actor, based on responses from fishers and fish trader groups interviewed in the dry- and rainy seasons. (Juseah, 2020)

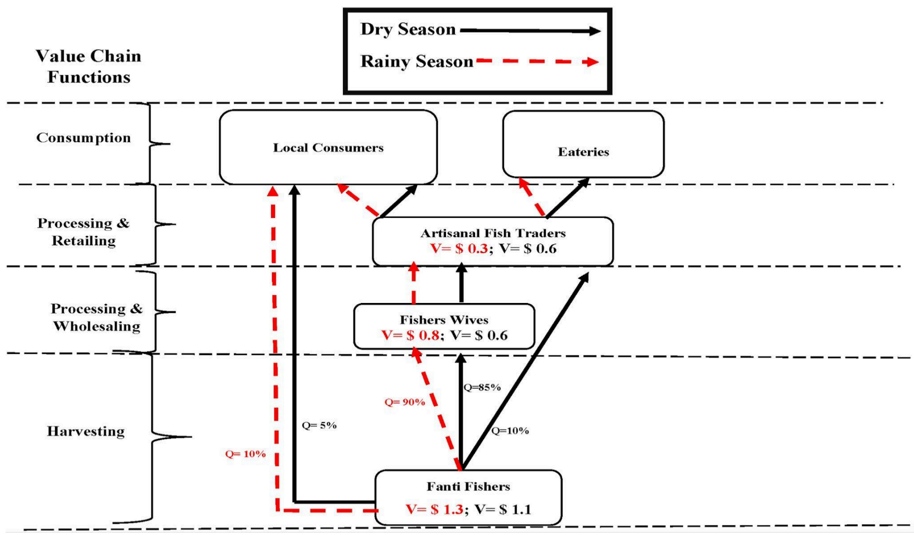


Figure 3: Fanti fishers value chain for shares (%) of bonny quantity traded and value-added by each actor, based on responses from fishers and fish trader groups interviewed in the dry and rainy seasons. (Juseah, 2020)

The SSF faces notable challenges in financing and fair pricing. Middlemen, including fishermen's wives and Korean traders, dominate the credit provision system, creating opaque and hierarchical value chains. For example, Kru fishers often struggle to accurately estimate the cost of fishing inputs provided by Korean traders, leaving them vulnerable to exploitative pricing practices. Similarly, the informal credit system supplied by wives ensures future access to fishing inputs but at lower repayment prices. The absence of access to formal credit services from banks, which typically require unattainable collateral, perpetuates fisher dependency on informal lenders. Despite these hurdles, the SSF remains vital to Liberia's economy, contributing to approximately 10% of the country's GDP (Belhabib et al., 2015).

There are 3,800 Kru canoes and 737 Fanti boats; therefore, to separate the crew and canoe owners from 11,000 fishers, we subtract 4,537 canoe boat owners from 11,000 to get the remaining 6,463 fishing crew members across the two types of boats (Jueseah et al, 2020). Kru boats require 1–4 crew members to operate, while Fanti boats require 4–26 crew members, with their larger size necessitating more labor (Jueseah et al, 2021). Given these differences, we calculated the proportion of fishing crew allocated to each type of boat. Based on the assumptions of maximum crew size, we estimate approximately 2,857 fishermen crew on Kru boats, while 3,606 fishermen crew on Fanti boats. It is important to note that these calculations assume maximum crew sizes (26 for Fanti boats and 4 for Kru boats). This assumption may overestimate the number of crew assigned to Fanti boats since, unlike Kru, not all boats are the same size. Consequently, this would affect the allocation of crew across boat types and the final income estimates. In addition, the difference between these figures and our model results stems from the fact that the reported data account for both fishing fleets, including crew and captain income, whereas our model only considers captain income to reflect their decision-making authority. As a result, our total estimate is higher than the model's projected value.

In terms of livelihoods, we will quantify the economic contributions of small-scale fisheries by calculating the total income of those employed in the sector, including fishermen, fish traders, and processors. This will account for both men and women involved in SSF, as well as family members who depend on the income generated by the sector. For instance, approximately 11,000 fishers are employed at a given wage, and another 22,000 individuals are involved in fish trading and processing, therefore, the total livelihoods supported by SSF can be calculated. Data from two Liberian fishing communities, Marshall and Westpoint, were used to estimate the average monthly ($USD) for canoe owners and crew members (Saye, 2024). Among canoe owners, the average income is $2,316.25 for Kru boats and $1,914.88 for Fanti boats. For crew members, the average monthly income is comparable, at $143.84 for Kru boats and $146.21 for Fanti boats.

Using these numbers, we then calculated the total income by multiplying the number of crew and canoe owners by their respective salaries. This resulted in an aggregate income of $9,212,700.88 for Kru fishers and $1,938,521.54 for Fanti fishers, amounting to a total of $11,151,222.42/month across both groups. These numbers highlight the economic significance of small-scale fisheries and their vital role in sustaining livelihoods for individuals and families in Liberia's coastal communities.

For the 22,000 individuals involved in fish processing and trading, we used a similar calculation method to estimate their contributions to the sector. For fish processors, Kru processors earn an average of $750 per month during the dry season and $250 per month during the rainy season (Jueseah et al, 2020). This results in an annual average monthly income of $500. In comparison, Fanti processors earn $2,154 per month during the dry season and $540 per month during the rainy season, with an average monthly income of $1,347 (Jueseah et al, 2020). Assuming an equal distribution of processors between Kru and Fanti, 5,500 each, the total monthly income for Kru processors is $2,750,000, and for Fanti processors, it is $7,408,500. Resulting in a total of $10,158,500/month for all fish processors. For fish traders, regardless of group, the average monthly income is $1,188.50, calculated from dry season earnings of $1,458 per month and rainy season earnings of $919 per month (Jueseah et al, 2020). Multiplying this by the 11,000 fish traders results in a total monthly income of $13,073,500/month.

Finally, combining the total monthly incomes for processors, traders, and fishers results in the overall economic contributions of these 33,000 individuals to Liberia's small-scale fisheries sector, amounting to $34,383,222.42/month or $412,598,668.98/year.

To further assess the important role of women in the sector, we also quantified the percentage of women involved in SSF. Since women comprise 60% of the workforce in Liberia's SSF, we can estimate the number of women directly involved in fishing, fish processing, and trading, as well as their contribution to household income and well-being (Jueseah et al, 2020). By calculating 60% of the total monthly income generated by the SSF industry, we find that women contribute approximately $20,629,933.45/month or $247,559,201.39/year to that income. This highlights the substantial impact women have in sustaining their families and supporting the broader economic health of the sector.

Qualitative Analysis

a. Human Rights

Historically, seafarers' rights have been relatively restricted, with labor protections at sea evolving more slowly than land-based industries (Teh et al., 2019). The International Labor Organization adopted the "Work in Fishing Convention" in 2007 to improve working conditions for fishers, covering areas like safety, accommodations, and fair treatment. However, it took nine years to reach the ten ratifications needed to take effect in 2017, and no additional states have joined since. The first and only vessel detention under the convention occurred in July 2018. The Law of the Sea is based on the principle of "freedom of the high seas," which grants flag States primary authority over vessels flying their flag. This means they are responsible for enforcing international law at sea. However, flag State enforcement alone has been insufficient, allowing human rights abuses on trawling vessels to persist (Nakemura et al., 2022). Globally, fundamental human rights are upheld through several international conventions and treaties. The 1948 Universal Declaration of Human Rights (UDHR) sets out these basic rights for all individuals, which are further reinforced by the legally binding 1966 International Covenant on Economic, Social, and Cultural Rights (ICESCR) and the International Covenant on Civil and Political Rights (ICCPR) (EJF, 2020).

Looking specifically at DWF, an independent consulting company did a complete analysis of the sectors' intersections with human rights and IUU fishing. They concluded that Human Rights, while tied to DWF, is very difficult to academically study (CEA, 2018). More specifically analyzing trawlers, an Environmental Justice Foundation (EJF) report indicates that human rights abuses are widespread, specifically among China's DWF fleet. Interviews with 116 Indonesian crew members revealed that 99% had witnessed wage deductions or withheld pay, 97% experienced debt bondage or document confiscation, and 89% worked excessive overtime. Additionally, 85% reported poor working and living conditions, 70% faced intimidation, and 58% experienced or witnessed physical violence. Similar patterns emerged in interviews with Ghanaian crew members on Chinese vessels in Ghana, where all reported poor living conditions, including inadequate food and water that led to illness, and 10 out of 10 had witnessed or suffered physical abuse by captains (EJF, 2020). Given Ghana's proximity to Liberia and the comparable operations of Chinese trawlers in both regions, these findings provide a concerning indication of the likely conditions aboard vessels operating off Liberia's coast.

Beyond human rights and labor concerns, crew members and fisheries observers report widespread illegal fishing in the trawl sector. In EJF's Ghana study, observer programs' effectiveness is questioned, as bribery, threats, and corruption hinder accurate reporting and enforcement of illegal activities at sea. While West Africa must take greater responsibility in strengthening fisheries governance, the burden also lies with foreign nations and trading blocs that benefit from its fisheries. The EU, for instance, could enhance enforcement by penalizing brokers and importers engaged in IUU practices, while China could be held accountable for the actions of its DWF fleet (Wuor & Mabon, 2022).

b. Illegal, Unregulated, and Unreported (IUU) Fishing

Illegal, Unreported, and Unregulated (IUU) fishing remains one of the most significant threats to Liberia's fisheries sector and marine ecosystems. Not only is IUU fishing a major governance and policy challenge in Liberia but also across the Gulf of Guinea (Wuor & Mabon, 2022). IUU fishing refers to all fishing activities that violate fisheries laws or operate outside of established regulations (Glassco, 2017). Illegal fishing includes activities such as fishing without a license, using prohibited gear, or operating in restricted areas like Marine Protected Areas (MPAs) or Liberia's Inshore Exclusion Zone (IEZ). Unreported fishing occurs when vessels intentionally misreport or underreport their catches to national fisheries authorities, obscuring the true scale of fish stock exploitation. Unregulated fishing refers to fishing in areas beyond national jurisdiction where there are no conservation or management measures in place, often conducted by vessels without a flag or from nations that are not part of Regional Fisheries Management Organizations (RFMOs) (Glassco, 2017). IUU fishing is a significant global issue, accounting for an estimated economic loss of $23 billion annually and representing 15–30% of the global fish catch (Glassco, 2017). In West Africa, over 40% of harvested fish stocks are unreported, threatening the food security of the 2.6 billion people worldwide who rely on fish protein (Glassco, 2017). In Liberia, where fisheries play a crucial role in both nutrition and economic livelihoods, IUU fishing poses a serious risk to sustainable development and long-term fisheries management.

Distant Water Fishing fleets, particularly those from China and the European Union, dominate Liberia's industrial fisheries sector, benefiting from weak enforcement and governance gaps. Between 1950 and 2010, an estimated 1.3 million metric tons of fish were illegally caught in Liberia's waters, representing over 60% of illegal capture fisheries, with an additional 249,000 metric tons of bycatch discarded (Glassco, 2017). Historically, Western European nations controlled industrial fishing in Liberia's waters from 1950 to 2010, after which Asian countries, particularly China and Korea, took over a substantial share (Glassco, 2017). Chinese fishing fleets have continued to contribute immensely to most of the IUU fishing activities in the EEZs of West African countries. Approximately 166,000 metric tonnes of illegal fish catch is associated with Chinese Distant Waters Fishing Operation (Glassco, 2017). These fleets engage in widespread IUU practices, such as overfishing, using prohibited gear, fishing in restricted areas, and misreporting catches. These fleets also maintain influence over Liberia's fisheries sector through opaque licensing agreements and political ties that undermine stricter regulatory enforcement. In Liberia alone, IUU fishing contributes to economic losses of approximately $75 million annually, displacing thousands of local fishers and undermining Liberia's domestic fishing industry (Glassco, 2017).

Beyond economic losses, IUU fishing poses severe threats to marine biodiversity and regional food security. In Liberia, key species such as barracuda, croakers, sharks, sardinella, and Ilisha Africana are heavily targeted for export to Europe, Asia, and North America. The unchecked exploitation of these fisheries intensifies stock depletion, disrupts marine ecosystems, and intensifies competition between industrial and artisanal fishers. Before the ban on pair trawling in 2007, Chinese trawlers were responsible for high discard rates and frequent conflicts with local fishers, destroying nets and encroaching into inshore exclusion zones. Despite regulatory efforts, weak legal frameworks, corruption, and resource constraints continue to hinder enforcement, allowing IUU practices to persist.

Efforts to combat IUU fishing in Liberia have included the introduction of a Monitoring, Control, and Surveillance (MCS) program under the West Africa Regional Fisheries Program, supported by the World Bank (Glassco, 2017). This initiative has helped strengthen enforcement through vessel monitoring systems (VMS), fisheries patrols, observer programs, and improved inspection protocols. However, enforcement remains weak due to limited resources and political will, as well as the continued ability of foreign fleets to operate without punishment. Without stricter enforcement, international accountability, and enhanced regional cooperation, IUU fishing will continue to threaten Liberia's fisheries sector, undermining both economic stability and marine conservation efforts.

c. Fishing Risk

To quantify the non-market impacts on fisher well-being, we will focus on the risks faced by fishers. Alternative policies that restrict or eliminate Distant Water Fleet trawlers could influence these risks by increasing local fish biomass and reducing the distance artisanal fishers must travel to secure their catch. To estimate the value of reducing fisher risk, we will use the Value of Statistical Life (VSL). VSL measures the rate at which an individual would give up money that he or she could spend on other goods and services to reduce current mortality risk. It is not the value of saving a particular individual's life with certainty, nor is it an indicator of an individual's moral or intrinsic worth. It represents the rate at which individuals are willing to exchange their own income for a small reduction in their own mortality risk in a particular time period. (Mayorga et al, 2009). The VSL for Liberia is calculated at USD $39,800 (adjusted for purchasing power parity) (Mayorga et al, 2009). To calculate the benefit of reducing fishing risk for individual fishers, we will apply the formula:

(%risk of fishing − %reduction of fishing risk) × VSL = benefit for one fisherman

The 22 member states of the Ministerial Conference on Fisheries Cooperation Among African States Bordering the Atlantic Ocean, of which Liberia is a part, have a yearly fatality rate of about 1,000 per 100,000 fishers. This is more than 12 times the rate used by the FAO in its most recent global estimate of fisher deaths (Pew, 2022). Therefore, if the risk of fishing one additional day is 1% but we reduce that risk by half, the calculation would be:

(0.01−0.005) × 39,800 × 11,000 (total # of fishers) = $2,189,000.00 USD

We assume a 50% reduction in fishing risk based on the expected decrease in long-distance travel and hazardous conditions once DWF trawlers are removed, as fishers can access more productive nearshore waters. This assumption is conservative yet reasonable, given historical trends showing that reduced competition leads to higher catch rates with less effort.

Historical trends in West African fisheries indicate that the removal of DWF trawlers could significantly alter fishing risks for artisanal fishers. Between 1950 and 2010, artisanal fishing efforts increased tenfold as local fleets expanded to compete with industrial fishing (Belhabib et al., 2018). Despite this, CPUE in artisanal fisheries declined by approximately 34%, with current CPUE levels 11 times lower than those of industrial fisheries (Belhabib et al., 2018). This decline has led to a well-documented trend where artisanal fishers are forced to spend more time at sea and travel further distances to maintain their catch levels.

In-person interviews of small-scale fishers and fishmongers were conducted in February and March 2023 across nine fishing communities in Rivercess (Cestos and Timbo), Sinoe (Downtown Fanti & Seegbeh), Grand Kru (Sess Town and Grandcess), and Maryland counties further confirmed this trend, with 87% of surveyed fishermen reporting that they now travel longer distances to find and catch fish. One respondent noted, "I travel farther these days as compared to the past" (Conservation International, 2023). This increased travel is particularly concerning for local fishers who primarily rely on non-motorized traditional canoes, many of whom aspire to transition to motorized boats to expand their range. If DWF trawlers were removed from Liberia's waters, several factors could influence the magnitude of risk for artisanal fishers. First, the reduction of industrial competition could lead to increased fish biomass, allowing artisanal fishers to catch more fish with less effort and reducing their need for long-distance travel. This would lower exposure to adverse weather, vessel fatigue, and accidents. Second, without industrial fleets depleting nearshore stocks, artisanal fishers may have access to more productive fishing grounds closer to shore, leading to lower operational costs, particularly for fuel.

While our calculations assume that no new fishers enter the market, the removal of DWF trawlers may instead contribute to Malthusian overfishing, where an influx of labor into the artisanal sector leads to increased fishing effort and resource depletion (Belhabib et al., 2018). If artisanal fleets continue expanding without regulation, CPUE may not recover, and fishers could still be forced into high-risk, long-distance operations to maintain their livelihoods. Studies emphasize the need for policies that prioritize artisanal fisheries due to their lower environmental impact compared to industrial fleets, but without adequate management, the potential benefits of reduced competition may be offset by increased artisanal fishing pressure. Therefore, while the elimination of DWF trawlers is expected to decrease direct risks associated with long-distance travel and industrial competition, the long-term safety and economic stability of artisanal fishers will depend on effective fisheries management.

d. Food Security

Food security is a serious concern in Liberia. According to the Global Hunger Index (GHI), Liberia's score is 31.9, reflecting serious food insecurity. 38.4% of the population - approximately 2,080,512 people - lack sufficient caloric intake (Global Hunger Index, 2024). Small-scale fisheries (SSF) play a vital role in providing essential micronutrients to local communities, however, the amount of fish caught by DWF trawlers and landed in Liberia is variable. This reduces access to crucial nutrients, such as protein, zinc, iron, omega-3s, and vitamins for Liberia's coastal populations (Conservation International, 2023). Deficiencies in these essential nutrients can cause severe health issues, including stunted growth, impaired physical and cognitive development, higher risk for cardiovascular disease, anemia, weakened immunity, greater susceptibility to infections, pregnancy complications, and neurobehavioral disorders (Hicks et al., 2019; Tako 2023). Enhancing access to locally caught fish could bridge this nutritional gap while promoting sustainable livelihoods.

It is important to note that Liberia's average per capita fish consumption is ~5kg. This is very low as the regional average per capita consumption of fish for the rest of West Africa is approximately 21 kg (ECOWAS Commission, 2020). Based on our limited data, to assess how this discrepancy in fish consumption affects nutrition, we assume that all fish consumed in Liberia are sardines. Although this is an oversimplification of the nutrient contribution of fish to Liberians' diets, we know that *Sardinella* spp. are a substantial part of the local food supply and provide a cheap source of protein (Yokie, A. A., 2019).

The nutrient profile of sardines was retrieved from Fishbase which uses data from FAO INFOODS and peer-reviewed literature (Fishbase 2021). Since both *Sardinella aurita* and *Sardinella maderensis* are used in our model, the average of the nutritional values was used. The nutrient profile of 100 g of sardines is 21g of protein, 11g of fat, 100 mg of calcium, 1.56 mg of iron, 51.3 mcg of selenium, 0.71 mg of zinc, 21.65 mg of vitamin A, 0.5 g of Omega 3 fatty acids, and 208 calories (Fishbase 2021). Studies on freshwater sardine processing show that smoking may affect nutrient content (primarily omega-3 fatty acids) (Chaula *et al.,* 2023). Still, the impacts are deemed small enough to ignore, considering limitations in quantifying this for our case study. Based on the assumption that Liberians are consuming 5 kg of fish in a year and that all of the fish are sardines this means that fish accounts for 1050 g of protein, 550 g of fat, 5000 mg of calcium, 78 mg of iron, 2565 mcg of selenium, 35.5 mg of zinc, 1082.5 mcg of Vitamin A, 25 g of omega 3 fatty acids, and 10,400 calories per person per year. This translates to 5.15% of their annual protein requirement, 3.43% of their annual fat requirement, 1.37% of their annual iron requirement, 12.77% of their annual selenium requirement, 1.02% of their annual zinc requirement, 0.4% of their vitamin A requirement, and 6.23% of their omega 3 fatty acid requirement.

Based on the results from our bioeconomic model, we found that under the 50% access fee scenario an additional 2,252 kg of sardines would be caught by SSF, under the 100% access fee scenario an additional 4,969 kg of sardines would be caught by SSF and under the ban scenario and an additional 34,540.8 kg would be caught by SSF in comparison to business as usual over a ten year time frame. With the assumption that all of the sardines would be consumed by fishermen and local communities in Liberia, this would provide an additional 4,684,160 calories under the 50% access fee scenario, an additional 71,834,864 calories to the small-scale fishing community under the 100% access fee scenario, and an additional 10,331,520 calories to the small-scale fishing community under the ban scenario. This also translates to an additional 472.92 kg of protein in the 50% access fee scenario, an additional 1,043.49 kg of protein in the 100% access fee scenario, and an additional 7,253.57 kg of protein in the ban scenario over the course of ten years when compared to the business as usual scenario. Although these numbers seem small, this is just the contribution that sardines will have in the diet of small-scale fishers in Liberia. We anticipate an increase in catch for many other species targeted by SSF, leading to an increased supply of calories and essential nutrients from fish for Liberian fishing communities as DWF effort declines under the 50% access fee, 100% access fee, or ban scenarios.

e. Fish Processor Health

Although fish processing provides a livelihood for 22,000 people in Liberia (Jueseah et al. 2021), there are serious health risks associated with smoking fish. Fish processors are exposed to smoke from wood fires for more than five hours a day. This prolonged exposure poses a significant risk to respiratory health, contributing to conditions such as asthma, chronic obstructive pulmonary disease, respiratory tract infections, and lung cancer. In addition, smoke exposure can cause impaired vision, eye infections, difficulty concentrating, dizziness, headaches, and skin rashes (Salvi and Brashier, 2014; Weyant et al., 2022). Currently, Liberia's air quality is poor, leading to respiratory illness which is one of the leading causes of death in the country (Dahn 2018; World Health Organization 2021). The health risks of fish processing disproportionately impact women and children because the industry is largely female-dominated, and many women bring their children along when smoking fish (Brickhill, 2020).

Recently, efforts have been made to improve the working conditions of fish processors in Liberia. In June of 2024, the Food and Agriculture Administration gifted Grand Bassa County a state-of-the-art fish processing facility. The facility was funded by the government of Japan and implemented by NaFAA. The facility uses FAO FFT technology that reduces smoke pollution and carcinogenic toxins, greatly reducing health risks for fish processors. In addition, the facility provides sanitary work conditions which also contribute to a healthier fish product (FAO, 2024). Although this is a step in the right direction, the facility only supports 1,000 fish processors. There are still 22,000 fish processors and traders throughout Liberia that continue to face poor working conditions to make a living. In the future, if access to the fishery changes and there is an increased availability of fish to small-scale fishers, more people may turn to fish processing as a livelihood, potentially increasing both the number of people exposed to hazardous conditions and the overall volume of smoke produced.

f. Trophic Value of Sardines

Sardines' trophic impacts serve as key indicators of ecosystem health due to their role as forage fish, essential prey for larger species. When fishing pressure causes sardine biomass to decline, the resulting loss of ecosystem services must be considered, as numerous dependent species may also suffer (Nissar et al., 2023). Sardines play a crucial role in the marine food web because they sustain many predators as lower trophic-level species. While it is challenging to attribute collapses to fishing because of strong natural fluctuations of these stocks, Essington et al. (2015) found that forage fish collapse can induce widespread ecological effects on dependent predators.

We use literature to value the current trophic services of Liberia's sardine fishery. A study estimates forage fish contribute USD 16.9 billion annually to global fisheries, including their role in "support of commercial predator fisheries" and "maintenance of biodiversity and ecosystem stability" (Pikitch et al., 2012). This estimate does not distinguish between sardine species, as they all serve similar trophic roles. To avoid double-counting findings from our model, we exclude the study's valuation of forage fisheries themselves, leaving the estimated value of "fisheries supported by forage fish" globally at USD 11.3 billion.

Another study on forage fish trophic impacts provides an appendix detailing the percentage of total fishery catch value attributable to trophic interactions. In Liberia it estimates that 50% of fishery value is derived from trophic predation, with total fishery catch value (TFCV) approximated via proxy data at 9,385,742 (Konar et al., 2019). This suggests that the trophic value of Liberia's fishery was approximately 4,692,871 USD. This study was done in 2006, and using the US Consumer Price Index to adjust, we would see 7,316,316.24 as a 2024 trophic value of sardines.

g. Shrimp Trawl Program

Coastal shrimp trawling comes with multifaceted concerns. Ecologically, it is associated with high bycatch rates, habitat destruction, and overfishing. The use of bottom trawls disturbs seabed ecosystems, harming benthic habitats and non-target species, including juvenile fish and marine invertebrates. Additionally, trawling contributes to declining fish stocks, disrupting marine food webs and threatening biodiversity.

Shrimp trawling also comes with socioeconomic concerns. Shrimp trawling supports livelihoods in many coastal communities but often leads to conflicts between industrial and small-scale fishers. The depletion of fish stocks due to bycatch can reduce resources available to artisanal fishers, undermining food security and long-term economic stability (Environmental Justice Foundation, 2003).

Liberia is not new to shrimp trawling and has allowed foreign trawlers to fish within the boundaries of what is now the IEZ until 2010. The IEZ was established to reduce the negative impacts imposed on small-scale fishers from trawlers. Recently, NaFAA has introduced a new pilot program, in part of their World Bank Sustainability Fisheries Management Plan funding, to allow a Senegalese shrimp trawling vessel into Liberia's IEZ.

While this new pilot program would closely collaborate with Liberia, any new trawling endeavor still poses these risks. Thus, extreme care should be taken when assessing the new pilot program of allowing a Senegalese shrimp trawling vessel in the IEZ. Small-scale fishers in Liberia have already voiced their concerns over the launch of this vessel. Thus, NaFAA must consider the potential social and environmental impacts of this pilot when designing the development of its coastal fisheries. Using case studies from Kenya (Munga et al., 2013), Senegal (Ziegler et al., 2011), and Mexico (Meltzer et al., 2012), we provide insight into key issues that arise in shrimp trawling fisheries and provide recommendations for NaFAA's consideration.

High Bycatch Rates and Marine Biodiversity Loss

A common issue across all three case studies was the exceptionally high rate of bycatch in shrimp trawling operations, leading to extensive waste and ecological damage. Bycatch includes non-target fish, juvenile species, marine mammals, sea turtles, and other invertebrates that are often discarded, dead or dying, back into the ocean.

- In Kenya, shrimp trawlers frequently caught commercially valuable fish species that were also targeted by artisanal fishers, reducing available fish stocks and undermining local livelihoods. The shrimp-to-bycatch ratio was poor, with bycatch levels increasing as shrimp stocks declined.
- In Senegal, industrial shrimp trawlers had an alarming bycatch rate of 88%, meaning that for every kilogram of shrimp caught, nearly nine kilograms of unwanted marine life were discarded. In contrast, Senegal's artisanal fishers had a much lower bycatch rate of 45%, showing that small-scale fisheries were more selective and less wasteful.
- In Mexico, the situation was even more severe, with bycatch rates averaging 85.9% and reaching as high as 99.24% in some trawls. This included endangered species such as sea turtles and sharks, which were inadvertently caught in trawl nets. Many of the species captured as juveniles were critical to local artisanal fisheries, meaning their removal from the ecosystem had long-term economic and ecological consequences.

Habitat Destruction and Overfishing Risks

Bottom trawling is highly destructive to marine habitats, as the heavy nets and trawl doors drag across the seafloor, disturbing sediment, damaging benthic ecosystems, and reducing the productivity of important fishing grounds. This disruption has far-reaching consequences for fish populations and the overall health of marine environments.

- Kenya's shrimp trawling operations resulted in significant habitat degradation, particularly in nursery areas for commercially important fish species. As fish habitats declined, shrimp landings fell from 550 metric tons in 2001 to just 250 metric tons in 2006, signaling overexploitation.
- In Mexico, industrial trawlers relied on otter trawls, which used heavy chains to stir up the seabed, making shrimp easier to catch. However, this method also destroyed fragile habitats such as coral reefs, seagrass beds, and soft-bottom ecosystems, reducing habitat complexity and biodiversity.
- Senegal's trawlers, despite operating offshore, still caused damage to important marine habitats, contributing to declining fish stocks and ecosystem instability. Additionally, their high fuel consumption made the fishery environmentally and economically inefficient.

Conflicts with Artisanal Fisheries

In all three case studies, shrimp trawling led to conflicts between industrial trawlers and artisanal fishers due to competition over resources and economic disruptions. Artisanal fisheries, which provide employment and food security for local communities, were negatively affected by industrial trawling practices.

- In Kenya, industrial shrimp trawlers frequently operated in areas also used by artisanal fishers, damaging their fishing gear and reducing fish stocks. Many small-scale fishers suffered financial losses as their catch volumes decreased. Additionally, trawlers' sale of low-value bycatch in local markets drove down fish prices, further harming artisanal fishers' earnings.

- Senegal's industrial shrimp trawlers employed significantly fewer people per ton of shrimp caught compared to the artisanal sector, highlighting the socio-economic inefficiency of industrial fishing. While industrial trawlers were capital-intensive and operated at a large scale, artisanal fishers provided more employment opportunities and economic benefits to local communities.
- In Mexico, shrimp trawler crews were found to illegally sell bycatch, undercutting the market for artisanal fishers. This, combined with habitat destruction and resource competition, exacerbated tensions between the two sectors.

Economic and Governance Challenges

Weak governance and poor enforcement of fisheries regulations contributed to unsustainable shrimp trawling in all three case studies. Many trawlers operated inefficiently, with high operational costs and limited oversight, leading to economic losses and environmental damage.

- In Kenya, fisheries regulations existed but were inconsistently enforced. This allowed trawlers to continue damaging marine ecosystems despite restrictions. The government eventually banned shrimp trawling in 2006 after continued pressure from artisanal fishers and environmental groups.
- Senegal's shrimp trawling industry was plagued by inefficiency. Industrial trawlers consumed large amounts of fuel, making operations expensive and unsustainable. Additionally, enforcement of fisheries regulations was weak, leading to continued overfishing and environmental degradation.
- In Mexico, compliance with bycatch reduction measures was a major challenge. Despite regulations requiring the use of Turtle Exclusion Devices (TEDs), many trawlers illegally removed them, resulting in continued harm to sea turtle populations. It was only after the U.S. banned Mexican shrimp imports in 2010 that enforcement improved.

Implications for Liberia

The experiences of Kenya, Senegal, and Mexico offer clear warnings and best practices for NaFAA as it considers shrimp trawling development. Key takeaways include:

1. **Implement Strong Bycatch Management Measures** –Bycatch reduction measures, such as the use of Bycatch Reduction Devices (BRDs) and Turtle Exclusion Devices (TEDs), are essential to reduce bycatch and protect marine biodiversity. NaFAA must ensure that any shrimp trawling operations mandate the use of such technologies to protect marine biodiversity and maintain healthy fish stocks.
2. **Protect Artisanal Fisheries** – Liberia has a predominantly artisanal fishing sector, meaning the introduction of shrimp trawling could disproportionately harm local livelihoods. To avoid conflicts, NaFAA should still establish trawl-free zones, restrict industrial trawlers from operating in key nearshore areas, and ensure fair resource allocation through participatory fisheries management.
3. **Enforce Habitat Protection Regulations** – In Liberia, many coastal fishers rely on inshore and estuarine habitats for their livelihoods. The destruction of these habitats could have severe long-term consequences for both fisheries productivity and

biodiversity. Before allowing shrimp trawling, NaFAA should conduct comprehensive environmental impact assessments and establish strict regulations to prevent habitat destruction, including spatial and seasonal fishing restrictions.

4. **Ensure Effective Governance and Monitoring** – Strengthening fisheries governance will be crucial to ensuring that any shrimp trawling operations are sustainable. Measures such as strict licensing, vessel monitoring systems (VMS), seasonal closures, and penalties for non-compliance could be utilized. Additionally, investing in research and stock assessments will help prevent overexploitation and ensure long-term economic viability.
5. **Assess Economic Viability** – Conduct cost-benefit analyses to determine if shrimp trawling is financially sustainable in Liberia and if alternative fisheries development, such as aquaculture, may be a better option.

Balancing economic development with environmental and social well-being is a challenging task. We cannot forgo any one for the other. But, by applying these lessons, NaFAA can make informed decisions about its fisheries sector, balancing economic development with environmental sustainability and social equity.

Discussion

Model Discussion of Limitations

While the scenarios presented in this analysis show that a reduction in DWF effort will lead to an increase in SSF catch per unit effort, this is the case with any fishery in which competition for the same target species exists (Seijo et al., 1998). However, with NaFAA's obligations to fund its operations with licensing fees from DWFs, an important distinction is whether this reduction in effort will happen gradually, as described mathematically by the bioeconomic model, or in an instantaneous fashion, as under the ban scenario. According to fisheries bioeconomics theory, a fleet's effort will not change within a fishery if they obtain zero net return, and they will reduce their effort if they experience net loss (Seijo et al., 1998). However, given the state of fisheries in West Africa, there is a chance that DWF trawling vessels do not gradually reduce their effort, but instead choose to immediately exit the fishery in favor of a neighboring country which will charge them less. If this were the case, then NaFAA would lose more money than if it were to marginally increase the access fee in an attempt to maintain DWF activity in its fishery.

One major limitation of this analysis is that while sardines are a vital resource for SSFs, they comprise only a small portion of the DWFs' total catch, and they catch less total weight of sardines than SSFs. This framework can be improved by incorporating different species targeted by both fleets in order to achieve more representative values to NaFAA of harvest by either fleet.

Our results also imply that regulatory approaches are incomplete at best in protecting Liberian fisheries and its fishers. Investment in SSF infrastructure must be prioritized in NaFAA's budget and planning. In-depth evaluations should be conducted to understand SSF needs and identify the best opportunities for development. NaFAA's decision-making process should also utilize a participatory action framework to collaborate with fishing communities to design effective programs. That being said, Liberia has begun this process. Government revenue from the industrial sub-sector grew sharply from $400,000 in 2011 to $6 million in 2013 (Jueseah et al, 2020). This growth can primarily be attributed to the efforts to reform fisheries management that started in 2011. Additional steps have been taken with the launch of The Liberia Sustainable Management of Fisheries Project (LSMFP), in 2021. With $40 million in funding from the World Bank's International Development Association (comprising $20 million in grants and $20 million in credit), the LSMFP aims to transform Liberia's fisheries sector through targeted interventions (World Bank Group, 2021). The project focuses on improving fishermen's and women's livelihoods by enhancing working conditions, infrastructure, and governance. It seeks to increase value-added processes for fish exports, ensuring higher economic returns for artisanal and industrial fisheries while reducing the sector's vulnerability to climate change and food insecurity. A key component of the LSMFP is establishing industrial and artisanal fish landing sites in Monrovia and artisanal landing sites in Margibi, Maryland, Grand Bassa, Sinoe, and Grand Kru counties (Jueseah et al, 2020). These landing sites are expected to modernize fish handling and processing, ensuring better product quality and opening new economic opportunities for coastal communities. By addressing systemic challenges and fostering sustainable practices, the LSMFP represents a crucial step toward the long-term growth and resilience of Liberia's fisheries sector.

Nonmarket Discussion and Limitations

Our nonmarket and qualitative analysis makes it clear that the current distant water fishing system in Liberia comes at a cost. While business-as-usual (BAU) distant water trawling generates revenue for NaFAA, it also creates significant environmental damage, health risks, and safety concerns, while undermining Liberia's small-scale fishing industry.

Not all of these costs can be measured in dollars, and data limitations mean our estimates are rough. However, the overall trend is clear: the financial and social costs of maintaining the distant water trawl fleet outweigh the benefits. Any policy that reduces the number of vessels in Liberian waters will help mitigate these negative effects.

At the same time, our analysis shows that not all of these problems come from the distant water fleet alone. The small-scale fishing industry needs investment in better management, tools, and technology. Raising access fees for trawlers would generate additional revenue that, in the short term, could support initiatives to address these challenges. Over time, this approach would likely push trawlers out of the market while funding efforts to strengthen the artisanal fishing sector. In the long run, this shift would lead to a more sustainable and resilient fishery.

Sensitivity Analysis

Cost parameter estimates were difficult, and created uncertainty in estimated NPV of the model (see Appendix Figure 10). While they didn't create intolerable uncertainty, the model was most sensitive to the costs of fishing in zone 2 and by the DWF fleet. This is due to the high harvest potential of the DWF fleet, and high allocation of harvest and effort by the SSF fleet in zone 2. Another point of interest is that our fee optimization was insensitive to our equity weighting parameter, β. This suggests that the revenue gained from access fees provide the greatest benefits to NaFAA at any value of β. This is consistent with our findings that the change in SSF catch and benefits are small when compared to the change in DWF catch and total benefits for NaFAA (see Table 1). However, NPV is highly sensitive to beta values, and so the distribution of values does not center around the mean (See Appendix Figure 11). This may change with more accurate parameter estimates, although is constrained by the algorithmic nature of non-linear optimization. Without any variation in the optimal fee, it was impossible to plot the response of the model output to parameter uncertainty.

Conclusion

This analysis demonstrates that, while not a perfect fix for curbing DWF trawling activity, a fee increase can be used in complement with other policy tools to safeguard SSFs in Liberia without major short term economic costs. Jueseah et. al (*forthcoming*) notes that maintaining the IEZ, securing tenure and access for SSFs should also be employed for fishery management in Liberia.

Our results found that, in the sardine fishery, an increased access to the DWF trawlers had modest impact on SSF effort, but did provide NaFAA with an appreciable increase in revenue gained over the 10 year period. In fact, the ending effort and B/BMSY decreases over the analysis period. These results are consistent with previous research that indicated that the sardine fishery is being over exploited (Yokie, A. A., 2019). While a reduction in DWF sardine fishing effort does have a positive impact on the health of the fishery over time, it alone is not enough for effective sardine management, as evidenced by the B/BMSY estimates at the end of the analysis period. While only two fee increase scenarios were evaluated in this project, this model can be used to explore many different access fee levels that NaFAA can weight the costs and benefits of.

While safeguarding the sardine fishery is essential for long-term sustainability, our findings do not suggest that small-scale fishers should be policed or penalized for their reliance on this resource. Sardines are a crucial nutrient source for Liberians and are easily caught due to their schooling behavior and minimal gear requirements, making them a natural target for SSFs, who report that sardines constitute 42% of their annual catch (NaFAA Statistics, 2024). Rather than restricting their access, NaFAA should prioritize investment in fishing infrastructure that enables SSFs to diversify their catch and reduce over-reliance on sardines. However, structural barriers such as informal credit systems and a lack of safety training continue to hinder fisher well-being. Many SSFs operate without access to life jackets, radios, or essential safety training, increasing their vulnerability at sea. Addressing these gaps through targeted investments in both infrastructure and training would enhance operational safety, decrease risk, improve livelihoods, and support a more resilient small-scale fishing sector. Balancing these efforts with broader fisheries management strategies is critical to ensuring the long-term sustainability of Liberia's fisheries and the well-being of its coastal communities. Further research regarding the long term impacts in investment in SSFs should be a priority for NaFAA and its partners to design effective strategies.

A full supply chain analysis of DWF trawler catch in Liberia is also needed. Currently, where the catch goes after it is landed is unknown. Understanding if the catch enters the Liberian market or not can influence NaFAA's approach to investing in SSFs. If the catch is part of the domestic market, then NaFAA will have to focus on rapidly increasing total catch of SSFs to replace the catch lost due to reduced or cessation of DWF catch. If DWF does not enter the Liberian market, then there will not be an immediate market shock, giving NaFAA the ability to focus on long-term strategies.

Liberia is endowed with rich natural resources within its EEZ, but along with the right to exploit these resources and provide access to foreign fleets, Liberia also has a responsibility to conserve and manage the resources under their jurisdiction (UNCLOS Art. 61). It is within the best interest of the Liberian people to develop governance and management frameworks that prioritize the long-term health of marine ecosystems while also safeguarding the livelihoods and food security of thousands of Liberians.

Appendix 1

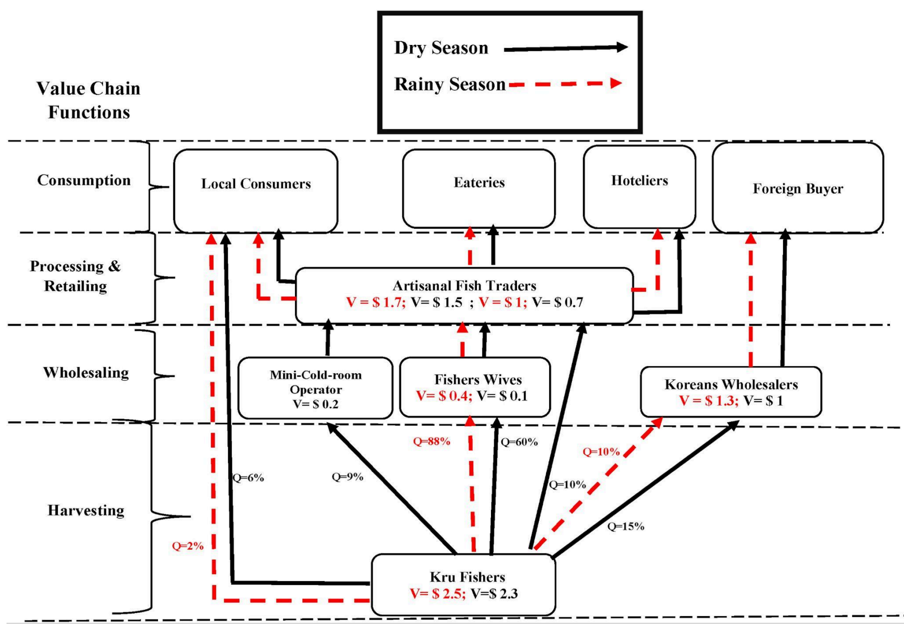


Figure 2: Kru fishers value chain for shares (%) of cassava fish traded and value-added by each actor, based on responses from fishers and fish trader groups interviewed in the dry- and rainy seasons. (Juseah, 2020)

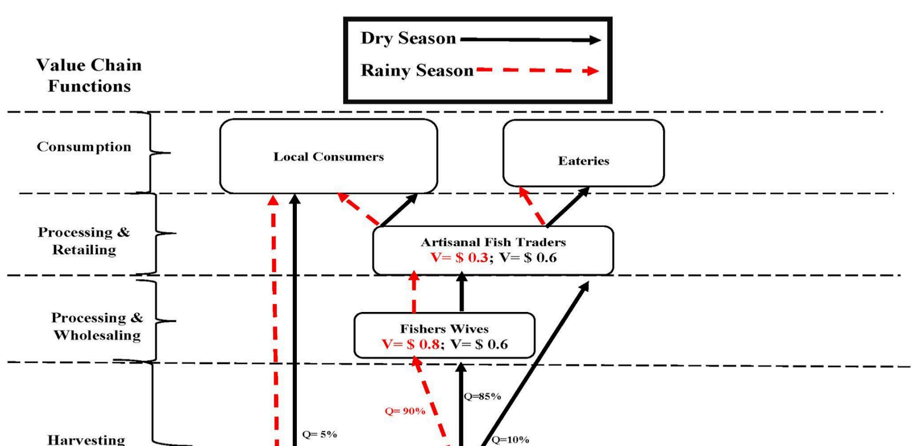


Figure 3: Fanti fishers value chain for shares (%) of bonny quantity traded and value-added by each actor, based on responses from fishers and fish trader groups interviewed in the dry and rainy seasons. (Juseah, 2020)

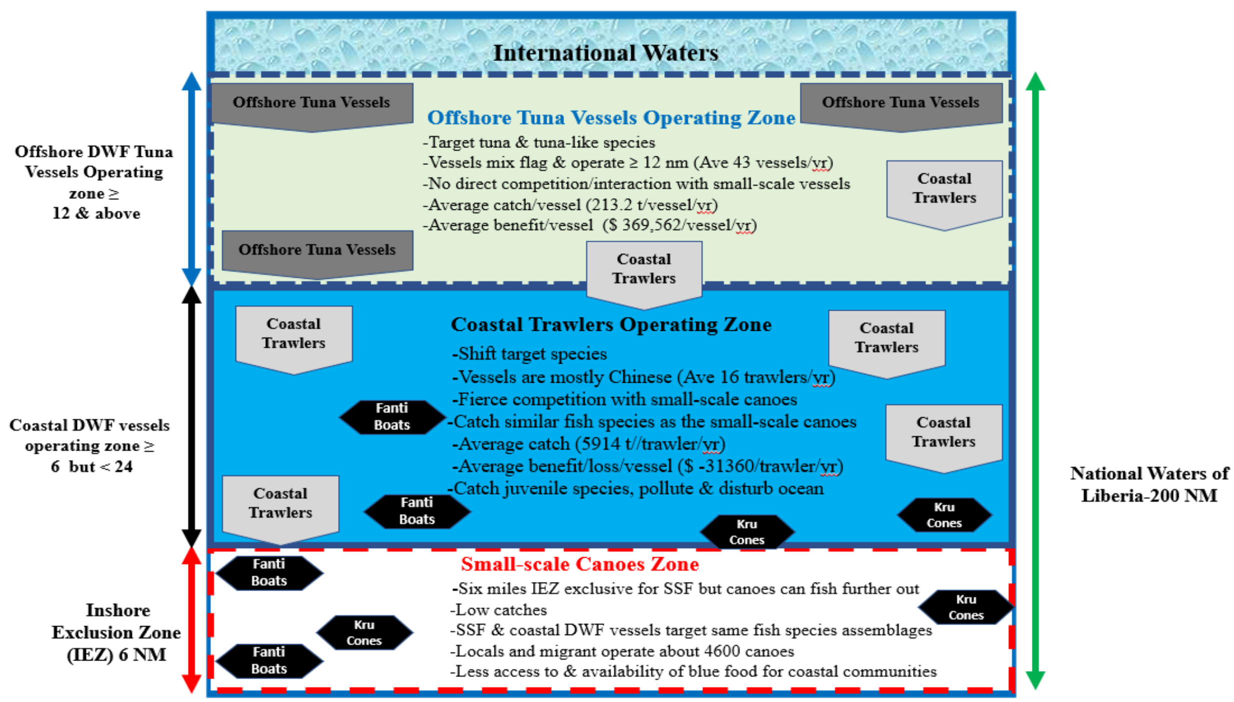


Figure 5: Relationship between the DWF and local fleet in Liberia's national waters (Conservation International, 2023)

Figure 6: Estimates of China's Distant Water Fishing Fleet

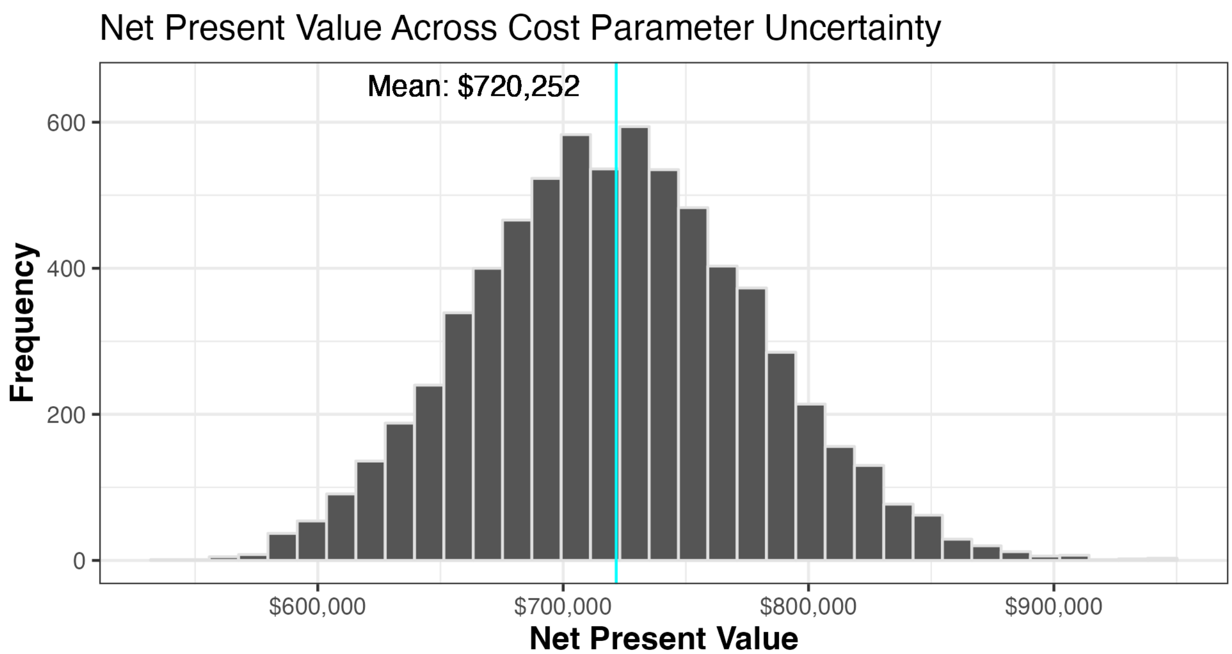


Figure 10: NPV uncertainty across varying cost parameter values.

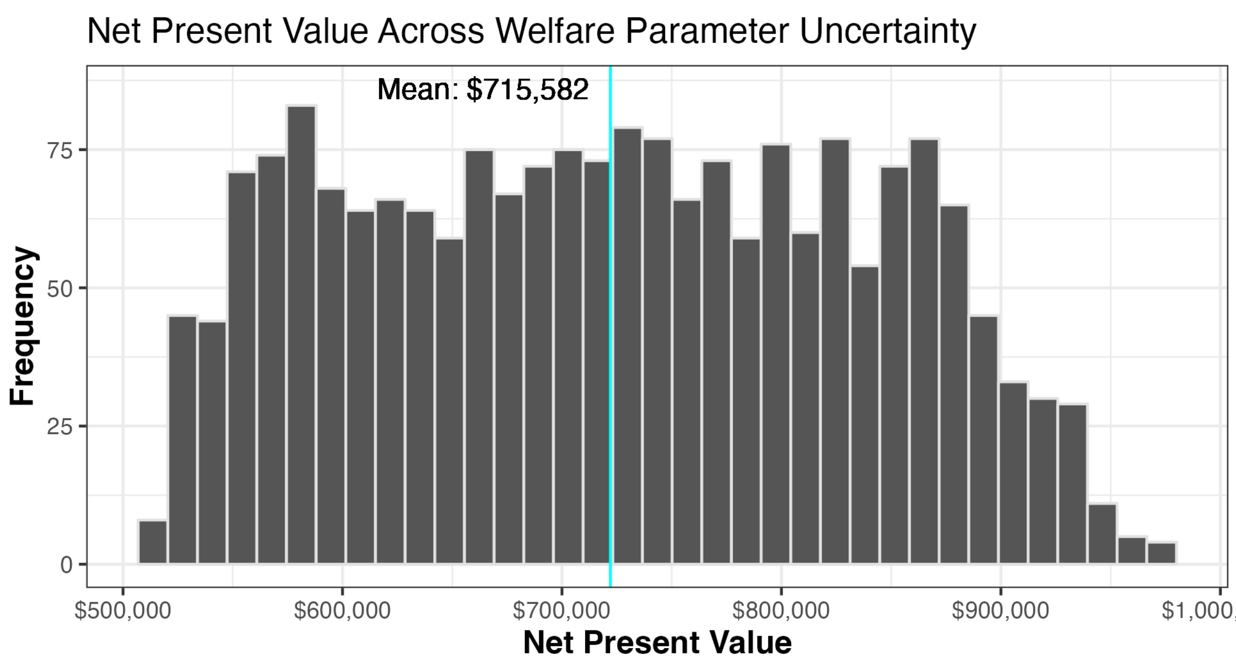


Figure 11: NPV uncertainty across varying beta and phi values. NPV is highly sensitive to beta values, and so the distribution of values does not center around the mean.

Figure 12: Calculations per each scenario of non-market impact categories

Impact Category	BAU	50%	100%	Ban

Biomass Loss	((25,000−16,000)/11)=818 tons/yr 818 tons = (818,000kg)(1.3USD) = **1,063,400$**	(1,063,400)(0.16)=-$ **893,256**	(1,063,400USD - (1,063,400USD x .03)) = **-1,031,498USD**	(1,063,400USD - (1,063,400USD x .16)) = **-250.87USD**
Juvenile Bycatch	(1529.86*0.7*0.446)*4.5) - (1529.86*0.7*0.446) = **-$1671.67USD**	(1449.69*0.7*0.446)*4.5) - (1449.69*0.7*0.446) **=-$1584.08USD**	(1353.48*0.7*0.446)*4.5) - (1353.48*0.7*0.446) = **-$1478.95 USD**	(415.02*0.7*0.446)*4.5) - (415.02*0.7*0.446) = **-$453.49USD**
Social Cost of Carbon	((4.65 *1387870)*(0.00110231))*(0.13) = **-$924.80 USD**	((4.65 *1315140)*(0.00110231))*(0.13) = **-$876.33 USD**	((4.65 *1227860)*(0.00110231))*(0.13) = **-$818.18 USD**	((4.65 *376500.0013)*(0.00110231))*(0.13) = **-$250.87 USD**

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