Thesis for the Degree of Master of Fisheries Science

A Game Theoretic Model and Solution for the Malindi Ungwana Bay Penaeid Conflict

by

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Pukyong National University

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Abstract

This is an empirical analysis of the Malindi Ungwana Bay prawn fishery in the coast of Kenya. A resource allocation problems is at the heart of the conflict between artisanal and commercial trawlers exploiting the prawn fishery in the bay. The Prawn Fishery Management plan by the government has not been fully implemented given its various shortcomings, leading to resource rent dissipation, stock externality, overfishing and a suboptimal fishery. Analysis of catch and CPUE data indicates the presence of important interactions between the fleets. Fisheries economics and game theory are applied here as the theoretical basis for solving this problem. Bioeconomic modelling is used to assess the status of resource utilization and profitability of the fishery. A two-player game theoretic model is then used to model the interaction between the fleets and to estimate an optimal resource allocation.

This study confirms that the fishery is operating sub-optimally. In the author's estimation, there are higher profits for cooperation than for non-cooperation among the fleets. These profits are obtained at comparatively lower levels of catch and effort and with better efficiency ratios in cooperation than in the non-cooperation scenario. Policy recommendations on optimal solutions to the conflict have been made. Management strategies for the maximization of resource rent and the sustainability of the fishery have also been suggested.

1 Introduction

Fisheries all over the world are severely overexploited (FAO, 2018). There are too many vessels pursuing too few fish, which causes conflicts among fishers, and fishing states in the case of straddling stocks as well as both national and international shared stocks (Lindroos and Pintassilgo, 2009).

A central idea in fisheries economics is that, in conditions of free access to fish resources and competition, the market will lead to non-optimal solutions in the use of particular resources. This open access nature of some fisheries and the presence of externalities in the capture leads to market equilibrium solutions that implicate the overexploitation of the resources and overcapacity in the industry (Coelho et al., 2011).

Whenever there are at least two fishers, fleets, countries or other agents harvesting a common fish resource, strategic interactions among these agents is inevitable. In such cases, the decisions of one fisher is not only influenced by the biological and socio-economic characteristics of the fishery, but also the behaviour of the other fishers or fleets exploiting the same fishery. The questions that often arise in such situations are: what are the bioeconomic consequences of such interactions; and are cooperative and non-cooperative behaviours biologically and economically efficient? (Lindroos and Pintassilgo, 2009).

Kenya’s coastal and marine fisheries are typically managed as open access with minimal entry controls and technical measures, which makes them vulnerable to over exploitation, potential resource depletion and myriad other associated problems such as stock externality and conflicts over shared stocks (Warui, 2014).

The Malindi Ungwana Bay prawn fishery is one of the important fishery resource in Kenya’s coast, however over the years conflicts between fishers exploiting the resource have led to serious dilemmas in the management of this resource. This work models the interaction between the artisanal and trawl fleets in the bay and applies game theoretic modelling to recommend an optimal solution to the conflict over allocation of the shared resource.

2 Background and Literature Review

2.1 Prawn and shrimp fisheries conflicts

According to the FAO (2016) shrimps and prawn are ranked second after salmon and trout in terms of global value of main fisheries commodities traded globally. These have been for many decades, the most traded fishery product and now have the highest catch trend in the world. The largest amount of shrimps and prawns produced globally are mainly from developing countries, and much of this production enters international trade (FAO, 2018).

In many nations, large-scale and small-scale prawn and shrimp fisheries operate within the same zones in the oceans and often target the same resource (Garcia, 1989; Banks and Macfayden, 2011). Most often though, large-scale prawn and shrimp fishing tend to affect small-scale fishers in many ways and at different levels, usually through increase in bycatch, significant habitat destruction and market supply challenges. In situations where there is overcapacity, this often leads to conflicts between the two scales of fishers (Abila, 2010).

The key management issues in global prawn and shrimp fishing are; bycatch and discards; overfishing and over-capacity; the rising costs of fishing, poor prices and low profitability; conflicts between large and small-scale fishers on resource allocation; physical impacts, environmental damages and destruction of habitats (Garcia, 1989; Gillett, 2008).

Within a number of national fisheries, industrial prawn fisheries initially develop with few or no conflicts with other fishers. They usually start out in the deeper offshore waters and are mainly undertaken at daytime. However, as fishers increase their efforts the stock biomass reduces, fishing operations progressively start to move inshore and most operations shift to night hours. This results in various types of conflicts with other inshore and coastal fishers over catch amounts, gear destruction and such, which usually lead some countries to take the drastic step of banning prawn trawling altogether (Garcia, 1989; Gillett, 2008).

The most common way of addressing conflicts arising from shared fishing ground in many countries has been to zone off fishing areas between large and small-scale operators, thereby reduce the physical impacts of large-scale fishers on small-scale fishers (Gillett, 2008). However, enforcement of such measures is usually very difficult and costly due to lack of adequate capacity for monitoring, control and surveillance (Abila, 2010).

Available literature on global shrimp fishing indicates that a number of other measures are either recommended or already put in place to address most of these management issues and challenges in many countries where they occur. These measures include; the use of by-catch reducing devices, discard control policies and use of turtle excluder devices; net modifications and mesh-size regulations; catch limits for fishing effort reduction, closed areas and gear restrictions; and in some cases, total trawling bans (Garcia, 1989; Gillett, 2008; Banks and Macfayden, 2011). Conflicts are addressed through zoning fishing areas; resource allocation between fishing operators and planned sharing of the fishing grounds through cooperation (Kelleher, 2005; Gillet, 2008).

2.2 Kenya marine fisheries sector

A large part of Kenya's marine fisheries is artisanal and small-scale in nature with fishers mostly doing it for subsistence and for trade as part of their livelihood. Resident and migrant artisanal fishers operate in the inshore waters while the offshore distant waters are exploited by various licenced Distant Waters Fishing Nations (DWFN) that target various Tuna and Tuna-like species (Hoof and Steins, 2017).

The industrial DWFN vessels are active throughout the year while the artisanal fishery depend strongly on the patterns and cycles of the Monsoon winds. Between September and March, are the Northeast monsoon winds during which the seas are warm and calm. Fishing activities are normally high in this season (Mbaru, 2012). Stormy winds and rough seas follow during the Southeast monsoon winds which occur between April and August, making the seas unfavourable for small vessels and light artisanal crafts (Warui, 2014).

There are generally three zones for fishing activities in the Kenyan waters. The first zone is the inshore areas that extends seawards up to five nautical miles. Fishing in this zone is reserved for artisanal and sports fishing. These zones are off limit for semi-industrial fishers and various other prohibited gears. Artisanal fishers and the recreational fishers are permitted to venture beyond these zones seawards (Hoorweg et al., 2009).

The second fishing zone is from five nautical miles extending seawards up to twelve nautical miles; the extent of the territorial waters. This is reserved for semi-industrial trawlers, which require a licence in order to fish in these areas (Hoorweg et al., 2009).

The third fishing zone is the Exclusive Economic Zone extending from the twelve nautical miles up to two hundred nautical miles. This zone is reserved for commercial and industrial fisheries. Licenced DWFN vessels operate in this zone (Hoof and Steins, 2017).

2.3 The Malindi Ungwana Bay fishery

2.3.1 Location

Malindi-Ungwana Bay (hereafter called Ungwana Bay) lies in the tropical Western Indian Ocean of the Kenyan coast (see Figure 1). It is generally characterized by a shallow continental shelf which ranges between 15km and 60 km offshore and is considered the widest continental shelf in Kenya’s coast (KMFRI, 2002). It is shared between the Coastal Counties of Kilifi and Tana River and is one among several but few rich inshore fishing grounds of the Kenyan coast (Maina, 2012; Munga, 2013; Ndegwa et. al, 2014).

The bay is about 200 km long extending from Mayungu (in Malindi) in the southern most end to Ras–Shaka (north of Kipini) in the northern end (Munga, 2013; Aloo et al., 2014). The total area of the bay is about 1200 km^2. Two of Kenya's largest river, the Sabaki and Tana Rivers discharge their waters into the bay at Malindi and Kipini respectively.

The mean depth of the bay is between 12 m at 1.5 nm and 18.0 m at 6.0 nm during the high tide. This depth increases to 100 m past 7 nm (KMFRI, 2002; Munga, 2013). The habitats along the bay include mangrove forests, sandy shores, islets, reefs and tidal flats (Munga et al., 2016). The bay has a total trawlable surface area of about 11,000 km^2.

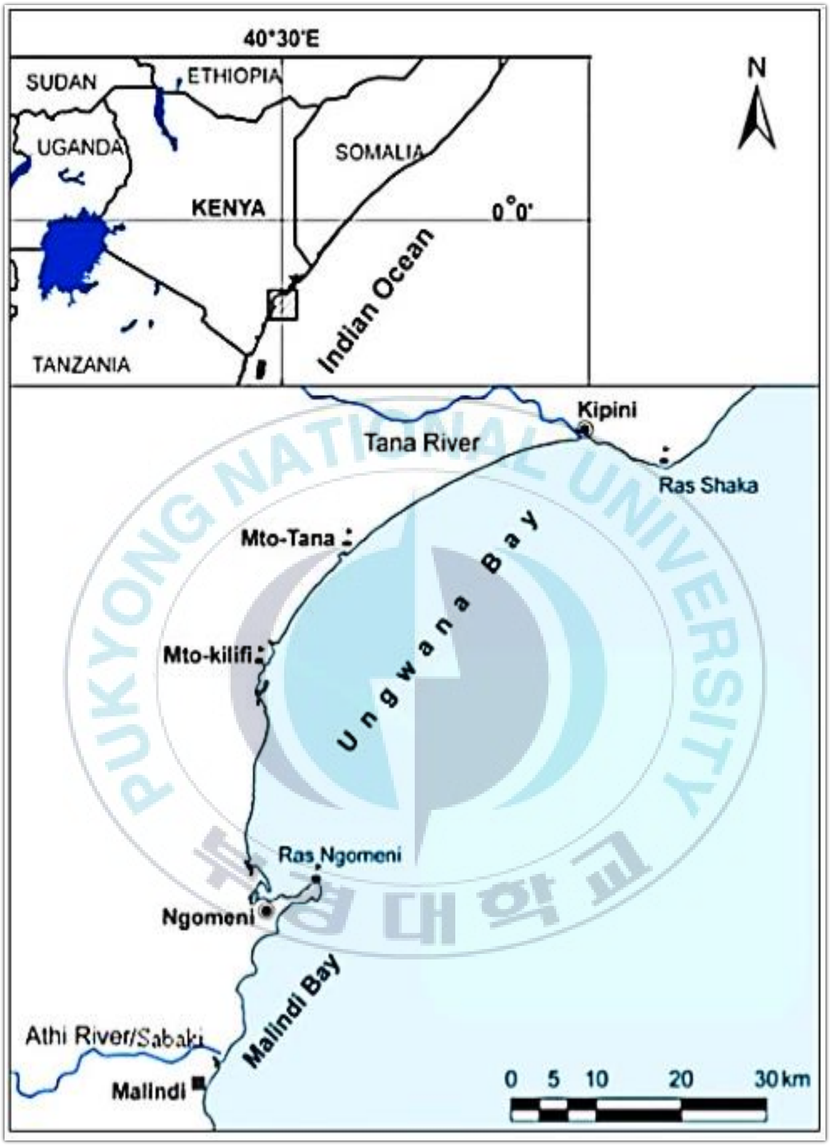

Figure 1: Map of Eastern Africa showing the location of the Ungwana Bay (Munga, 2013).

The bay is a species-rich ecosystem with a rich variety of crustacean, mollusc, elasmobranch and teleost species. Its richness is because of unique estuarine attributes owing to Rivers Tana and Sabaki which favour the critical processes of water circulation, fresh water input and vital nutrients supply and hence favouring the occurrence of prawns (State Department of Fisheries, 2016a). Estuaries are recognized for their role in producing valuable resources like fishes, molluscs, crustaceans and prawns (Munga et al., 2016).

2.3.2 Malindi-Ungwana Bay prawn fishery

The Malindi- Ungwana Bay hosts the Kenya's only industrial prawn fishery which is also the largest in the east Africa region (Hoof and Steins, 2017). The main fishers in the Bay are the small-scale artisanal fishers and the semi-industrial commercial trawlers (Munga, 2013). Besides provision of food, employment and income, as an estuarine environment, the fishery is also of great importance in the coast for its ecological and biodiversity purposes (Munga et al., 2016).

Approximately 400 artisanal fishers operate at the main landing sites within the bay (State Department of Fisheries, 2016a). The bay provides livelihood for the fishers who are mainly drawn from the adjacent coastal Counties. These resident and other migrant artisanal fishers utilize the inshore waters up to 3nm (Fulanda et al., 2011). The artisanal fishers in the bay are restricted to less than

3nm due to their lack of proper vessels and gear that they could use to access deeper offshore waters (Munga et al., 2016).

The artisanal vessels are generally fairly homogenous, most of which are traditional crafts with few numbers of dhows and motorboats. These are various forms of dugout canoes or plank wood boats that can be fitted with outriggers and may either have sails or be motorized by light engines. The bigger vessels tend to be planked (Fulanda et al., 2009; Warui, 2014). These artisanal crafts have various lengths between 4 m and 11 m long (Warui, 2014).

A mix of traditional and modern gear are used in the artisanal fishery, these include various forms of nylon netting such as beach-seines, small-meshed gill nets, floating gill nets (Fulanda et al., 2009, 2011; del Elst and Everett, 2015). The gear choice usually depend with the target species of any particular fisher. The main fishing gear used by the artisanal fishers targeting prawns are prawn seines made of monofilament or multifilament materials as well as cast nets, gill nets and prawn traps deployed from small wooden boats (KMFRI, 2017).

Semi-industrial prawn trawlers mainly fish in the shallow areas around Ungwana Bay as well as in the nearby deep seas, where besides targeting prawns, they also fish for various export oriented pelagic fish. The prawn fishery management plan restricts them to trawling from 5 nm and up to 200 nm only (Government of Kenya, 2011). These trawlers are mostly private business entities operated in joined venture with foreign companies (del Elst and Everett, 2015).

The commercial prawn trawling in the bay has been going on for the last three decades. The numbers of licensed prawn trawlers has been varying between 4 and 6 in the previous years with an exception of some years in which there were more than 6 trawlers fishing in the bay. A typical prawn trawler in this fishery has an average length that varies between 25 and 40 metres and is mainly operated using double rigged otter trawls fitted with booms (KMFRI, 2007). The vessels have engines of up to 1500 hp and catch storage between 30 and 350 t (del Elst and Everett, 2015). The trawl net mesh sizes are between 55 and <40 mm. The inclusion of turtle excluder devices has been compulsory and in legislation since 2003. The trawlers trips range between 16 and 30 days in an 8-10 month season (del Elst and Everett, 2015).

According to the Kenya Marine and Fisheries Research Institute (KMFRI, 2017) prawn catches by the trawlers averaged between 350 t and 650 t per annum over the last decade or so. Recent estimates put the Maximum Sustainable Yield of Malindi-Ungwana Bay prawn fishery at about 433 t (Fulanda et al., 2011). Based on the MSY, KMFRI has over the years recommended that a maximum of only 4 trawlers be licensed to fish in the fishery, and that a total allowable catch be enforced with respect to the MSY level.

2.3.3 *Historic trends of the fishery*

The artisanal fishery in the bay can be traced to the 9th century, it seems to coincide with the time of the rise of Eastern Africa Indian Ocean trade undertaken by the Arabians, Persians and Indian merchants (Fulanda et al., 2011; Munga et al., 2012).

Fishing expeditions and trawl surveys by the Kenyan government and international development partners in the 1960s and 70s established the existence of viable stocks of the shallow water penaeid prawns in the area. This discovery promoted the establishment and later development of artisanal and semi-industrial prawn fisheries in this area, eventually making it the most dominant prawn fishing area on the Kenyan coast (KMFRI, 2002; Munga et al., 2016).

Similar with other tropical countries, the prawn fisheries of Ungwana Bay have faced many challenges over the past decade. These include; numerous conflicts between the artisanal and the semi-industrial fisheries (del Elst and Everett, 2015); environmental concerns over the effects of bottom trawling; high amount of bycatch, including juvenile fish of high value commercial fish species; discards and other endangered organisms, concerns of potential overfishing by trawlers above the maximum sustainable yield, among other issues (Abila, 2010).

Artisanal fishing and semi-industrial trawling have coexisted for long in this fishery, with the artisanal fishers exploiting various fish and shell fish species available there while the trawlers exploit the prawn stocks. Escalation of conflicts between these two groups of fishers caused the government to ban bottom trawling in 2006. This ban was only lifted in 2011 with the introduction of the prawn fishery management plan that reduced the number of allowable trawlers in the bay to four vessels.

2.3.4 The biology of the fishery

The estuarine conditions of the bay have made it the ideal habitat for various species of the family Penaeidae; the tiger prawn (*Panaeus monodon*), Indian white prawn (*P. indicus*), the green tiger prawn (*P. semisulcutus*), the speckled shrimp (*Metapenaeus monoceros*) and peregrine shrimp (*Metapenaeus stebbingi*) (Kalama, 2013; Munga et al., 2016; Hoof & Steins, 2017; KMFRI, 2017). These five are the main targeted species of prawn in this fishery.

The distribution of the prawns in the bay is such that there is an abundance of the same in the shallow estuaries of the rivers Sabaki and Tana, decreases occur with depth seawards (Kimani, 2016). There is also higher biomass and catch during the Southeast

Monsoon season than during the Northeast Monsoon seasons that tend to be drier (Kimani et al., 2016; Munga et al., 2016).

Previous studies conducted on the status of the prawn fishery before the closure and ban on bottom trawling in 2006 estimated the maximum sustainable yield of the prawn fishery at 352- 446 t (Fulanda et al., 2011). These were against mean annual landings of 60 t and 330 t for the artisanal and trawl fishery respectively. This meant that by 2005, while the artisanal fishery might have been underexploited, the trawl prawn fishery was considered fully exploited. For all the species of prawn targeted in the fishery, current fishing mortality is considered to be higher than that recommended for maximum sustainable yield (KMFRI, 2017).

Recent stock assessments by KMFRI (2017) indicates exploitation rates (F/Z) of between 0.59 and 0.76 for the prawn species. This is above their recommended levels of 0.5 and indicates that the fishery is heavily overfished (biological overfishing) and is producing way below the maximum sustainable yield. The spawning stock biomass per recruitment (SSB/R) estimate of 0.06 is below that required for the MSY of 0.2 which according to them indicates that the prawn stocks are being fished unsustainably (KMFRI, 2017).

KMFRI; the lead national marine research agency further recommends a reduction of the fishing mortality from 1.99 to 1.05, which is an 89.5% reduction in order to bring the stocks within their estimated maximum sustainable yield (KMFRI, 2017).

2.3.5 The economics of the fishery

It is estimated that, the annual turnover of Kenya's shallow water prawn fishery is about KSh. 284 million. The commercial trawlers have the largest share of 84.5% while the artisanal fishers share the remainder (Abila, 2010).

The total annual landings from small-scale prawn fishery is approximately 363.5 t based on the 2013- 2014 state Department of Fisheries catch assessment survey data (Hoof and Steins, 2017). Malindi-Ungwana bay contributes up to 40% of the catch. The current estimated average value for a kg of prawns is KSh. 600 (US$ 6)(State Department of Fisheries, 2016b). The Ungwana bay fishery therefore generates up to KSh.127 million (US$ 1.234 million) per annum (KMFRI, 2017).

There are at least nine different groups of beneficiaries from the Ungwana Bay prawn fishing. These are; trawler companies, artisanal fishers, traders, transporters, hotels, non-fishing households, Governments (Central and County Government). The main socioeconomic benefits include; Income to fishers, dealers and trawlers; Foreign exchange; Employment, trading and support services; Sea food; Fees, taxes and revenue to governments and related agencies; related services such as hotels and others (Abila, 2010).

Most of the catch from this fishery is sold in the export market. Prawns and other shellfish such as squids, cuttlefish and crabs from Ungwana Bay fishery are exported to European Union countries, with Italy, the Netherlands, Spain and Portugal as the leading destinations. The finfish are sold in the local markets at the landing sites, and to the urban coastal markets and hotels by the dealers operating mainly from Malindi and Mombasa, with a few exceptions of high value fish that are exported (Abila, 2010).

2.3.6 Conflict between artisanal and semi-industrial trawler fleets

The artisanal and the semi industrial trawl fishers in Ungwana Bay compete for similar and overlapping fish resources. This conflict that has been in existence for a long time and remains unresolved over several decades (Munga et al., 2014). The conflict has attracted concerns from fisheries experts, conservationists and environmental groups.

There have been several causes to the conflict between the small-scale fishers and the industrial prawn fishers in Ungwana Bay. The main ones are;

- The destruction of artisanal fishers' gear by bottom trawlers, and the failure to pay compensation for them appropriately (Ochiewo et al., 2008; Mbaru, 2012; Munga et al., 2011, Aloo et al., 2014, Omukoto et al., 2014)

- The artisanal fishers blame the prawn trawlers for the decline in fish and prawn catches, high amounts of by-catch and discards and that the trawlers prefer to sell their bycatch in Malindi and Mombasa towns rather than sell it to the local communities (Abila, 2010; Kalama, 2013; del Elst & Everett, 2015). This imposes on the artisanal fishers an incidental externality which threatens their livelihoods by denying them the access to the fish both for trade and for food. It also causes the local market prices of fish to fall (Vanreusel & Munga, 2013; Munga et al., 2016)

- The artisanal fishers are against the prawn trawlers fishing in the shallow areas near the shore, the prawn fisheries management plan outlaws the same. On the contrary, the trawlers have a tendency to get into the 3 nm and commonly up to 1.5 nm (Fulanda et al., 2011; Munga et al., 2014). This is because shallow water prawns and shrimps are more concentrated towards the inshore and their biomass decreases with increased distance from the shore seawards (Garcia and Reste, 1981; KMFRI, 2007; Munga et al., 2014).

In September 2006, the government banned bottom trawling in the bay as a result of the escalation of conflict between the artisanal fishers and the semi-industrial trawlers. The ban was only lifted in mid of 2011 which saw trawling resume in 2012 (Munga et al., 2014). In order to address these conflicts and better manage the fishery, the prawn fisheries management plan was developed in 2011 (Munga, 2013; Munga et al., 2014).

The artisanal fishery is expected to grow with population increase in the country and therefore active and immediate strategic decision making is crucial to reduce if not resolve the resource user conflict in the future (Munga, 2013; Munga et al., 2016). It is also important to understand the dynamics and benefits around sharing of the common resource among various users.

2.3.7 The Prawn Fishery Management Plan

The Prawn Fishery Management Plan was the first fisheries management plan in Kenya. It was developed to address and curb among others, overcapacity in the fishery and to provide an equitable access to the resource (Government of Kenya, 2011; Mbaru, 2012; K’Omolo, 2015). It covers aspects of the exploitation of prawn in the deep and shallow waters of the Kenyan coast and highlights the various regulations concerned with the operations of fishing fleets and the use of various permitted fishing gear by fleet operators.

The management plan further provides technical measures and some institutional frameworks to ensure that the prawn fishery is economically viable and that exploitation is done sustainably (Maina, 2012). It sets a limit on the number of allowable trawlers and bans trawling within three nautical miles from the coast, while providing for small-scale fishers to fish only between the shore line and the 3 nm distance (Government of Kenya, 2011). It prescribes closed fishing seasons, gear modifications and various other regulations for prawn fishery in the Kenyan coast.

Although the management plan is considered as being operational (Japp, 2011), it has not been fully adhered to and lacks the socio-political support among various stakeholders in the Ungwana bay prawn fishery due to various failures and issues that it has not addressed effectively. These include:

- Failure to address important socio-political issues between the trawlers and artisanal fishers such as access to and allocations of the fishery resource (Hoof and Steins, 2017). These issues revolve around rights of access to the various zones in the fishery and interactions among the fleets within the fishery. The interactions have been about the composition of catch of the trawl fleets, gear interactions and perceived responsibilities to the status of stocks within the inshore zones and the economics of the catch.

Apparently, interactions among the fleets are the genesis of the conflicts in the bay (Munga et al., 2012).

- Failure to adequately address and incorporate vital small-scale prawn fisheries aspects (KMFRI, 2017).
- Failure to incorporate adequate scientific information which implies that the management plan is based on precautionary principles rather than the much appropriate ecosystem approach to fisheries (Japp, 2011; Munga, 2013; KMFRI, 2017).
- Failure to understand the operations of the artisanal prawn fishery and their fishing areas (Onyango, 2015; State Department of Fisheries, 2016a).
- Lack of adequate measures for the management of the small-scale prawn fishery (State Department of Fisheries, 2016a).

The Prawn Management Plan has been viewed as based on wrong objectives and that it is limited as an effective tool for achieving optimal benefits in the prawn fishery (Warui, 2014). It is also considered as lacking a defined timeline and the appropriate legal structures and mechanisms that would ease its implementations (K'Omolo, 2015).

2.4 Bioeconomics and Game Theory in Fisheries Management

There are several analytical tools applicable in the analysis of shared fish and shellfish stocks. Among these are bioeconomic and game theory models (Villasante and Sumaila, 2010).

Bioeconomics applies economic theory and concepts to model dynamic natural systems (Grisel, 2012). They are applied in fisheries management in order to capture the essential parameters of a fishery, to study them and predict the evolution of the resource (Berachi, 2003; Wang and Toumasators, 2015). They provide important set of tools that are used to determine sustainable catch, effort levels and exploitation regimes.

Bioeconomic models specify the biological dynamics of the fishery and integrate into them the economic production parameters of the fishery in order to produce these optimal management strategies of a stock (Milon et al., 1999). One important objective of optimal fisheries management is the implementation of strategies that maximize the net present values of economic rents from any fishery. These are considered as the optimal harvest strategy for any fishery resource (Kar and Chakraborty, 2011).

The bioeconomic theory of any fishery reconciles the biological dynamics of the stock with the economics of the respective industry in order to provide the socially optimum level of effort and the corresponding catches (Milon et al., 1999). Fisheries managers are primarily interested in stock sustainability followed by fisheries profitability among other economic and biological objectives.

In the exploitation of a common fish resource, strategic interactions do happen between the agents who can be fishers, fleets, countries or even coalitions of countries. These interactions often lead to conflicts given that the various resource users have different objectives for the exploitation of the common stock. In such scenario, game theory is applied to understand the characteristics of each player‘s strategy or behaviour, and allow fisheries economists to predict the possible solutions to the game (conflict) (Bailey et al., 2010).

Game theory provides a formal tool for modelling and analysing the strategic interactions between finite numbers of agents sharing an exploited resource as they seek to maximize their desired outcomes (Sumaila, 1997; Grisel, 2012). In fisheries economics, game theory is important in understanding the strategic choices between various agents who share a fish stock (Villasante & Sumaila, 2010). These strategic interactions are usually interpreted as how harvests by any one agent affect fishing behaviour and fishing strategies of all or some of the other agents exploiting the same fish stock (Grønbæk, 2000).

Game theory typically lays out two possible strategies in any game: non-cooperative and cooperative. In a non-cooperative game, commitments (promises, agreements and threats) are not enforceable upon the players. These games focus on the strategic choices of the individual players: how each player plays their game and what strategies they choose to achieve their goals. On the other hand, a game is cooperative if the agreed upon commitments are fully binding and enforceable.

Game theory and bioeconomic modelling help fisheries managers to analyze, conceptualize and understand how fishers make decisions and how these individual decisions affect the individual and aggregate benefits and losses in the fishery (Grisel, 2012). Policy interests of managers are to develop incentives that provide for each agent in the fishery to make self-interested decisions that result in overall net-benefits and sustainable outcomes for all.

It is possible for game theory to provide efficient and effective tools that can be used to analyze and understand the interactions and resulting externalities occurring in the context of strategic, multi-agent, interactive decision-making.

There are numerous examples from all over the world on the application of game theory in solving fisheries conflict or at least in mitigating them. A good example is the application of game theory modelling as part of the strategy to understand and assist

Bissau Guinean and Senegalese fishers in Cacine Guinea-Bissau to discuss solutions that were key in the conservation of the West African saw fish. Through the application of game theory techniques, fishers built their own solutions that were key in the action towards conservation of their marine resources (IUCN, 2016).

Game theory has been used in several cases to explain the origin of fisheries conflicts and the emergence of cooperation that can lead to successful conflict free fisheries (Lindroos and Pintassilgo, 2009). When used with bioeconomic modelling, they can provide the theoretical basis for solving fisher disputes concerning access and allocation of fishing resources. Wang & Toumasators (2015) apply these to find a solution for the Northeast Atlantic Mackerel dispute between Iceland and coastal states of EU, Norway and Faroe Islands.

Hutton and Sumaila (2002) use game theoretic modelling and bio-economic analysis to explore the cooperative versus non-cooperative management of the west coast hake stock in South Africa. By simulating the effects of quota restrictions on the long line and the demersal trawl fleets that compete for the hake stocks fishing rights, they are able to make recommendations on how the fishing rights could be allocated better for optimal utilization of the resource. Further, they provide important recommendations on economic policy measures concerning this particular fishery.

Game theory and bioeconomics are highly predictive and have been applied to estimate the benefits of either cooperation or noncooperation management in shared stocks. Villasante and Sumaila (2010) model the interaction between Argentine and United Kingdom fleets exploring the Argentine shortfin squid in the Patagonian large marine ecosystem. The authors predict high economic benefits obtainable through cooperation that would enhance the sustainability of the fishery and maintain the squid stock abundance above the reference points recommended by stock scientists.

3 Thesis Statement

3.1 Problem Statement

The prawn fishery at Ungwana Bay is a domestically shared stock targeted by artisanal fishers and semi-industrial prawn trawlers as the main players. The trawlers always exhaust their prawn share early while the prawn share targeted by artisanal fishers is still healthy.

The Prawn Management Plan fails to address the recurrent and inherent conflict between these two resource users. The two groups in the fishery are asymmetrical in general exploitation habits and have very different objectives in their participation in the fishery hence complicating the possibility of managing them with the Prawn Fishery Management Plan.

Previous studies have been confined to addressing the conflict through attempting to identify the gaps in various laws and policies in place. There is little that has been done or documented about the strategic interactions of the stakeholders in this fishery.

3.2 Overall Objective

The main objective is to determine whether some change in the management policy for the prawn fishery might better manage the conflict between artisanal fishers and semi-industrial prawn trawlers in order to increase the social and economic benefits obtained from the fishery while ensuring its sustainability.

3.3 Specific Goals

i. To develop a game-theoretic bioeconomic model of the fishery;

ii. To use this model to evaluate the benefits to each group of participants in the fishery of non-cooperative and co-operative approaches;

iii. To use this analysis in recommending viable, optimal management strategies that will increase benefits to all parties while ensuring sustainability of the resource.

4 Methods

4.1 Model

This study develops a bioeconomic model of the fishery, and then uses this model in a game-theoretic framework to model strategic interactions between the two players in the fishery.

4.1.1 The Biological model

The surplus production model is based on the work of Gordon (1954) and Schaefer (1957), who developed a basic bioeconomic model for fisheries management. The version described here follows the approach laid out by Flaaten (2016). The model is chosen given that it is simple and does not require a lot of data which in these nature of fisheries can be a challenge.

In the application of this model, the artisanal and commercial trawl fisheries are considered as two distinct fisheries sharing a common stock. The objective of this decision is to understand the behaviour and attributes of each fishery and to provide reference points for modelling their interaction as well as take into consideration the fact that the harvest function of each fishery is different.

The model is based on the logistic growth equation:

$$F(X) = rX\left(1 - \frac{X}{K}\right) \quad (1)$$

Where F(X) is the natural growth (surplus biomass) per unit of time; X is the prawn stock size while K is the fisheries carrying capacity. This equation is a parabolic growth curve as a function of X.

In order to find the maximum natural growth and the corresponding stock biomass, the first order derivative of equation (1) is set equal to zero:

$$\frac{dF(X)}{d(X)} = r\left(1 - \frac{2X}{K}\right) = 0 \qquad (2)$$

Solving for X

$$X_{MSY} = \frac{K}{2}$$

Schaefer’s catch equation being a bilinear short-term harvest function assumes that the applied effort will always take away a constant proportion of the biomass.

The harvest function:

$$H(E, X) = qEX \qquad (3)$$

Where H is the catch per unit of time measured is terms of biomass; E is the fishing effort and q is the catchability coefficient of the respective fleet.

The sustainable yield in this case occurs at the point where the rate of harvest equals the natural growth; at this point, the rate of change of biomass is equals to zero. Therefore based on equation (1) and equation (3):

$$\frac{dX}{dt} = F(X) - H(E,X) = 0$$

This implies that at equilibrium:

$$qEX = rX\left(1 - \frac{X}{K}\right)$$

Solving for X, we obtain biomass at equilibrium to be:

$$X = K\left(1 - \frac{qE}{r}\right) \quad (4)$$

The long-term catch equation is obtained by inserting equation (4) into equation (3):

$$H(E) = qKE\left(1 - \frac{q}{r}E\right) = qKE - \frac{q^2KE^2}{r} \quad (5)$$

This equation (5) can further be rewritten as follows:

$$H(E) = aE - bE^2 \quad (6)$$

Where $a = qK$ and $b = \frac{q^2\,K}{r}$

The effort at the maximum sustainable yield (E_{msy}) can be obtained by taking the derivative of eq. 6 with respect to effort (E) and setting it equal to 0, which finds:

$$E_{msy} = \frac{a}{2b} \quad (7)$$

Substituting in the initial values of a and b we rewrite it as:

$$E_{msy} = \frac{r}{2q}$$

The output (harvest) at MSY is then obtained as:

$$H(E_{msy}) = \frac{a^2}{4b} \quad (8)$$

And then substituting in the values of a and b we can also rewrite this as:

$$H\left(E_{msy}\right) = \frac{rK}{4}$$

4.1.2 The Economic model

Assuming constant prices, a perfectly elastic demand for fish and unit marginal cost of effort for the vessels in the two different fleets, total revenue (TR) as a function of effort (E) will be:

$$TR(E) = pH(E) \quad (9)$$

Where p denotes a constant price per unit harvest (H) of prawn.

Assuming a unit cost of fishing effort and a linear relationship between total cost of fishing effort and effort, total cost of fishing effort (TC) of the fleet can be expressed as:

$$TC(E) = cE \quad (10)$$

Where c is the unit cost of effort and in this case includes the variable and fixed costs as well as the opportunity cost of labour and capital; and E is fishing effort.

The profit (resource rent) of the fishery ($\boldsymbol{\pi}$) as a function of the fishing effort (E) is given as:

$$\pi(E) = TR(E) - TC(E) \tag{11}$$

We can find the level of effort where economic returns are maximize by taking the derivative of this expression and setting it equal to zero:

$$\pi'(E) = 0 \quad \text{or} \quad \frac{dTR(E)}{dE} = \frac{dTC(E)}{dE}$$

Therefore the effort at the MEY is:

$$E_{MEY} = \left(\frac{a - \frac{c}{p}}{2b}\right) \tag{12}$$

Substituting in the initial expressions of a and b

$$E_{MEY} = \frac{r}{2q}\left(1 - \frac{c}{pqK}\right)$$

These expressions for MEY apply only in the case where there is a single fishing fleet. In the current case with two fleets, MEY will depend on the relative catching power (q) and unit costs of effort (c) of each fleet. These solutions will be found numerically in this application of the model, as described below (see section).

4.1.3 The Game theoretic model

The bioeconomic model described above is applied in a two-player game-theoretic framework in order to explore and analyse the outcomes of either cooperation or non-cooperation in the exploitation of the fishery. The players in the game are the small-scale artisanal fishers and the semi-industrial prawn trawlers that operate in the bay. This model assumed that the fishery is organised around these two main fleets.

Non-cooperation

In this scenario, the players do not cooperate with each other, instead each player seeks to maximize their own objective function, which is the player's own profit (from equation 11). This maximization is subject to the actions of the other player, as the other player's fishing effort and harvest will reduce the size of the stock.

In cases where both fleets have the same catchability (q) and unit cost of effort (c), a solution to the model can be found analytically using a reaction function, which defines each player's strategy as a function of the other player's strategy (Lindroos and Pintassilgo, 2009). However, given the asymmetrical fleets in this case, the model is herein solved numerically, as follows. First, a simulation of the fishery is initialized using the calculated biomass estimate (see below) and fishing effort levels in 2005. This simulation is then run for 100 years to ensure it would come to an equilibrium. A numerical search program (Solver in Microsoft Excel) is then used to find the numerical solution using an iterative approach, by:

(1) Finding the profit-maximizing effort for the artisanal fleet given the effort of the trawl fleet;
(2) Finding the profit-maximizing effort for the trawl fleet given the effort of the artisanal fleet; and
(3) Repeating steps 1 and 2 until a stable solution is reached, i.e., when no further changes are observed in the optimal effort levels with further numerical searches.

In this non-cooperative case the assumption is that the stock variable is controlled by nature and only indirectly by the player's choice of effort levels.

Cooperation

In the cooperative solution, the players collaboratively agree on the amount of fishing effort to be exerted by each fleet in order to maximize a joint objective function, which is the total profit of the two fleets together.

Given the linear nature of my model, this cooperative solution resulted in the trawl fishery being shut down and the artisanal fleet being allocated its MEY amount of effort and harvest, because the artisanal fleet is marginally more profitable than the trawl fleet. This is unlikely to be a realistic or acceptable outcome as it would raise concerns about the equitable distribution of the benefits of the fishery.

To explore more realistic options, a numerical search is conducted to find a set of solutions where: (1) a fixed percentage of catch (ranging from 0-100%, in increments of 10 percentage points) is allocated to one fleet, with the remainder of the catch allocated to the other fleet; and (2) the aggregate profit of the two fleets is maximized subject to the constraint in point 1 being met.

In the cooperative scenario, it is assumed that by maximizing with respect to the prevailing stock levels, the players are able to take in to direct account the marginal stock effects (Sumaila, 1997).

4.2 Assumptions

An assumption is made that there is a single stock of Penaeids existing in the Ungwana Bay prawn fishery. This implies that there is no significant immigration or emigration of Penaeids into and out of the area, so the stocks remain the same in the bay. This assumption is based on a mitochondrial genetic study of the estuarine and offshore prawn specimen of the bay that found no diversity or separation between them implying the presence of a single stock (del Elst and Everett 2015).

Population parameters of the prawn fishery such as growth, recruitment, and natural mortality are assumed to be constant.

The study also assumes that all economic parameters remain constant through time, and that the price per kilogram of fish is the same for each fleet. Capital in each fishing fleet is assumed to be perfectly malleable.

Given that the artisanal fishing fleet differs widely in its general characteristics, gear used, engine size and various attributes, the following assumptions on the general characteristics of the fleet are used: a standard craft in the fishery is non-mechanized and non-motorized, measuring about 7 m long; a fishing season lasts 200 days each year; the fishing season lasts for 10- 11 months after which the vessels are dry docked for repairs or shelter from strong monsoon winds and during various festive seasons of the year (Fulanda et al., 2011; Warui, 2014).

It is further assumed that the vessels in the trawler fleet are homogenous in their attributes, operational costs and their trawling behaviour and catch profiles. The annual number of days operated by trawlers was estimated at 204 (Fulanda et al., 2011; del Elst and Everett, 2015).

For the purpose of the game theory model, it is assumed that fishers within each fleet are cooperative agents, so non-cooperation only occurs between the artisanal vessels and the semi-industrial trawlers. An assumption is also made that the two players operate as two groups and that the behaviour of one player in either group is taken as a representation of the behaviour of all the other players in the same group. The players in either group are thus assumed to have homogenous behaviour. Further, an assumption is made that the moves of each player are finite and that information flow is perfect such that either of the two players can keep track of the strategy adopted by the rival player.

4.3 Parameter Estimations

4.3.1 Biological parameters

The estimation of the biological parameters of the fishery was done using historic data on catch and catch per unit effort (CPUE) for each fleet during 1985-2005. This study adopted the catch-effort data provided in Fulanda et al., (2011) from their report on fishery use and resource allocation in the Ungwana Bay. Further comparisons and inferences on the trends in the fishery are obtained from various other economic studies focusing on the fishery over the same period (Ochiewo, 2006; Abila, 2010; Fulanda et al., 2011; Swaleh et al, 2015).

A first set of estimates of the intrinsic rate of increase (r), carrying capacity (K), and catchability coefficient for the two fleets combined (q) was obtained using Walters and Hilborn's (1976) linear regression method, which does not require an assumption that the fishery is at equilibrium.

Having obtained these initial estimates, they were then refined further using Hilborn and Walters's (Hilborn and Walters, 1992) time-series estimation method, by which the fishery is simulated and then a numerical search routine (Solver in Microsoft Excel) used to find a combination of parameters that minimize the sum of squared deviations between observed CPUE values and those simulated by the model. This second method resulted in some small refinement of the parameter estimates.

The catchability coefficient estimated using the above methods was a single value for the two fleets combined, but separate estimates were required. To find initial estimates of these separate catchabilities, the observed CPUE for each fleet in each year were divided by the biomass in that year as predicted by the dynamic model that used the parameter estimates above, the mean of each year's estimated q for each fleet was then taken as the initial estimate. The time-series estimation described above was then revised to include observed fishing effort, estimated biomass, and the initial estimates of catchability for the two separate fleets. This revised model was then used to refine the estimated q values to (1) further reduce the sum of squared deviations between observed and predicted values and (2) improve the visual fit of observed and predicted values.

4.3.2 Economic parameters

Estimates of unit costs of effort were obtained and inferred from economic evaluations reports on the trawl fleet in the bay as reported in Abila (2010) and those for the artisanal fleet in the

Kenyan coast as presented by Ochiewo (2006) and Warui (2014), over the time period from which catches and CPUE data was being studied (1985- 2005). From these, profiles of the components of the operational and fixed costs were constructed. Estimates were then made based on the operations of the fleet over the period (Ochiewo, 2006; Hoorweg et al., 2009;Abila, 2010; Warui, 2014).

The overall average price of prawn over the period was estimated as KSh. 600 per kilogram based on economic reports on the fishery over the given period (Ochiewo, 2006; Abila, 2010).

5 Numerical Analysis and Results

5.1 Catch and CPUE trends of the fleets

From 1985 to 2005, catch and CPUE trends of the two fleets show different trends from year to subsequent year. There are no clear patterns over the period but there are some very distinct observations.

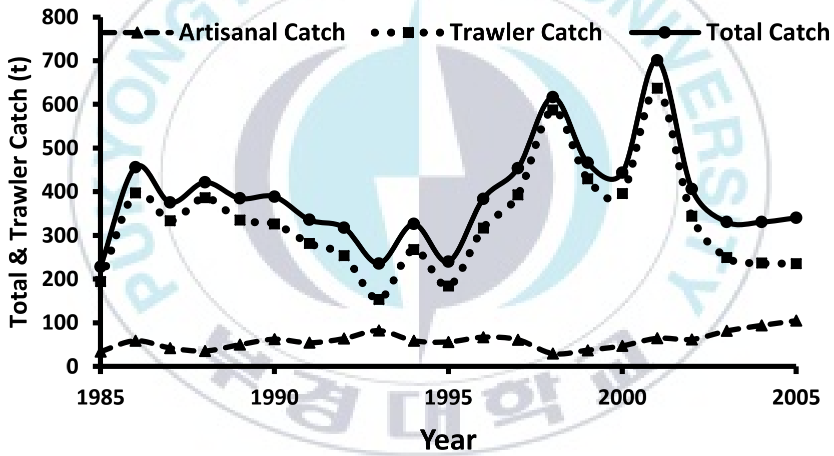

Figure 2: Catch trends in the Ungwana Bay Prawn fishery during 1985- 2005.

In general, for the total catches, there is a rise in catches from 1985 to 1986 after which the catches show a steady decline annually up to about 1993. From 1995, for three subsequent years, there is a steady marked rise in the catches from the fishery, a trend that continues up to 1998. This is then followed by a drop in the catches in the years 1999 and 2000, then an all-time high peak in 2001 after which the total catches fall again in 2002 and 2003 and then appear to level off in 2004 and 2005.

The catches for the two fleets show differing trends over the years. In the artisanal fleet, there are low catches in the years 1985, 1988 and the lowest occurring in 1998. Catches in several years between 1986 and 1996 range between 50 and 70 t. There is a steep rise in catches from the year 2002 until the year 2005 where the catches peak at slightly above 104 t.

In the trawl fleet, there is a general declining trend in the catches from 1986 up to 1993 where the catches reach their lowest point for these years. The catches show a rise from the year 1995 until 1998 after which they fall in the following years and then peak for the period at 636 t in 2001. There is then a gradual drop in the harvest through the years 2002 up to 2005.

While the pattern of catches in the two fleets show no clear comparisons, it is notable that while trawl catches show a declining trend in the period between 1990 and 1993, there is a rise in the artisanal catches over the same period.

Important however is the observation that total catches from the fishery seem to comprise of trawl catches in a large portion. This is evident in the clear similarity in the paths that the total and trawler catches follow; rising and falling at about the same period in time as shown in Figure 2.

There is a moderately negative correlation of -0.43 between the trawler catches and the artisanal catches between the period 1985-2005. During this period, a rise in trawler catches seems to coincide with a period of either falling artisanal catches or low artisanal catches. This trend is particularly clear in the batch of years comprising 1987-1990, 1990- 1994, 1997- 2000 and 2002-2003.

Notable also is the fact that artisanal catches show a clear rising trend from the year 1998 to 2005 which is not observed in the trawl fishery. In the trawl fishery, during the same period there are two declines in the total catches. The first decline happens from 1998 up to 2000, followed by a steep rise in the year 2001 after which the catches decline all through to the year 2005.

Figure 3 below shows the evolution of effort in the fleets over the 1985- 2005 period. The artisanal effort has been rising significantly over the years. There is a gradual rise in artisanal effort between 1985 and 1995 followed by a slight deep between 1996 and 1997, a rise in 1998 up to 1999 followed by a fall in the effort in the years 2000- 2001. The artisanal effort then rises rapidly for two subsequent years after which it levels off in 2004 in to 2005.

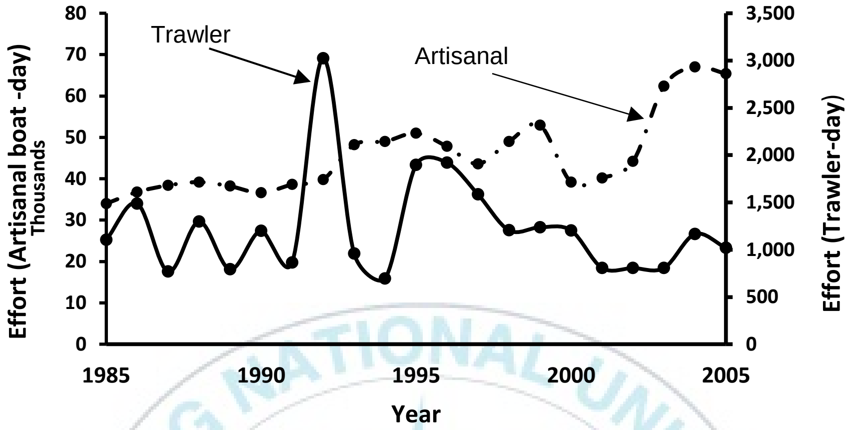

Figure 3: Annual trends in fleet effort in the Ungwana Bay Prawn fishery from 1985- 2005.

The trawler effort follows a different path and pattern over the same period, rising and falling sequentially from 1985 until the year 1992 when the trawler effort peaks at its highest level for the period. In 1994, the trawler effort falls again only to pick markedly in 1995 after which there is a notable downwards trend in the trawler effort levels over the subsequent years only to rise slightly in 2004 followed by a decline in 2005.

Comparing the two fleets, there is a notable trend in that while there is a general levelling in the trawler effort over the period apart from the years 1992 and 1996, there is a marked rise in artisanal fishing effort over the same period.

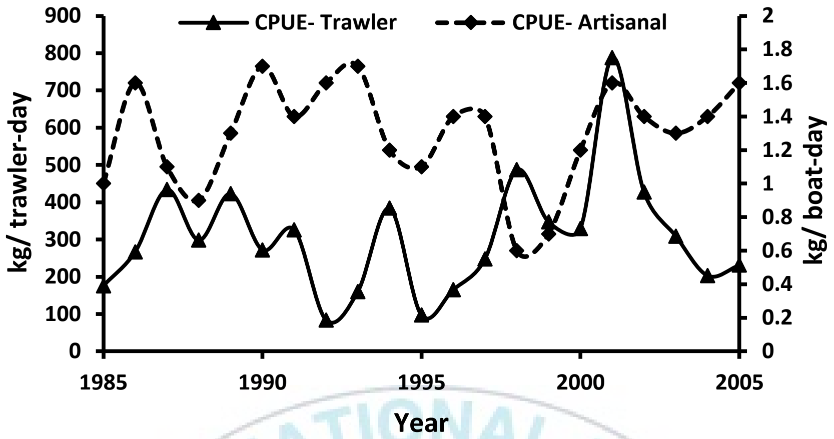

Figure 4: Annual trends in the CPUE of the fleets during the years 1985- 2005.

5.2 Parameter estimates

The biological parameter estimates are shown in table 1 below while the biomass estimates of the Malindi Ungwana Bay prawn stock are shown in table 2.

Table 1: Biological parameter estimates.

Parameter Description	**Carrying capacity**	**Starting Biomass**	**Intrinsic growth rate**	**Catchability (trawlers)**	**Catchability (artisanal)**
Symbol	K	Xo	r	qT	qA
Estimate	1,399 t	662 t	1.34	0.405×10^{-4}	1.62×10^{-6}

Table 2: Estimates of the biomass of the Malindi Ungwana Bay prawn stocks.

Year	Estimated Total Biomass (t)	Total Catch (t)
1985	662.2	228.3
1986	692.0	456.2
1987	903.3	375.6
1988	801.7	421.9
1989	954.6	384.7
1990	841.4	388.6
1991	944.7	335.7
1992	139.1	317.7
1993	242.3	235.5
1994	423.6	326.1
1995	459.9	240.0
1996	481.2	383.7
1997	562.4	453.9
1998	694.8	616.2
1999	756.7	466.3
2000	806.2	443.6
2001	948.6	701.0
2002	981.2	406.0
2003	954.8	330.9
2004	807.8	330.3
2005	846.8	340.3

The biomass estimates show variability from year to year. There is first increasing biomass from the starting biomass of 662 t, increasing over the years until it peaks in 1989. There is then a drastic drop in the biomass in the year 1992 which coincides with the year with the lowest CPUE for the trawlers. The biomass then rises gradually over the next years until it peaks again in the year 2003. In the year 2004 and 2005, the biomass drops a bit but remains nevertheless high at levels above 800 t.

The unit cost of effort for the period of study is estimated as KSh. 513 for a unit cost of the effort of one artisanal boat day and KSh. 128,125 for a unit cost of the effort of one trawler day.

5.3 MSY and MEY

Based on an assumption of a single prawn stock being exploited by the two different fleets, the estimated MSY of the prawn fishery is 470 t while the estimated MEY is 403 t (Table 3). The estimated effort for the two fleets are computed on the assumption that the fleets depend exclusively on prawn catches. Estimated effort for the trawler fleet is given in trawler-days while effort for the artisanal fleet is in boat-days.

Table 3. Estimates of effort at MSY and MEY for one fleet assume that the other fleet is not operating.

Parameter	Variable	
	MSY	MEY
Yield (t)	470	403
Effort trawler-days	1,660	1,033
Effort boat-days	413,161	257,638

5.4 Game theoretic model solution

The results from the biomass estimations and the static bioeconomic model are used to find the solution to the game theoretic model. A non-discounted simulation is performed from the year 2006 for a period of 100 years in order to observe the annual revenue flows corresponding to the two fleets in the scenario of cooperation and non-cooperation. The biomass at the end of 2005 is considered as the beginning biomass in the year 2006.

Higher profits are obtained under cooperation of the fleets than under non-cooperation. At a negotiated Pareto optimum 50% of catch for either fleets, the annual profits per fleet are significantly higher than those of non-cooperation. These profits for cooperation are also at lower levels of catch than those for non-cooperation as shown in table 4. The table also shows other stable cooperation solutions that involve allocating various proportions of catches to the two fleets.

Table 4: Summary of maximum annual payoffs at different allocations of catch.

% Catch allocated to Artisanal	Effort Artisanal (boat-days)	Effort Trawlers (Trawler-days)	Catch Artisanal (t)	Catch Trawl (t)	Profit Artisanal (m. KSh.)	Profit Trawlers (m. KSh.)
0	-	1,033	-	403.1	-	109.4
0.10	25,746	930	40.3	362.8	11.0	98.5
0.20	51,496	827	80.6	322.5	21.9	87.5
0.30	77,250	723	120.9	282.1	32.8	76.6
0.40	103,008	620	161.2	241.8	43.8	65.6
0.50	128,770	517	201.5	201.5	54.8	54.8
0.60	154,536	413	241.8	161.2	65.7	43.8
0.70	180,306	310	282.1	120.9	76.7	32.8
0.80	206,079	207	322.5	80.6	87.7	21.9
0.90	231,857	103	362.8	40.3	98.6	10.9
1	257,638	-	403.1	-	109.6	-
Non-coop	171,889	688	228.4	227.9	48.8	48.6

NB: m.KSh. – million Kenya shillings

Table 5: Comparison of non-cooperation and cooperation payoffs at maximized profits.

Strategy	Artisanal Effort (Boat-days)	Trawler Effort (Trawler-days)	Artisanal Catch (t)	Trawler Catch (t)	Artisanal Profits m.KSh	Trawler Profits m.KSh
Non-cooperation	171,889	688	228	227	48.7	48.5
Cooperation	128,770	517	201	201	54.7	54.7

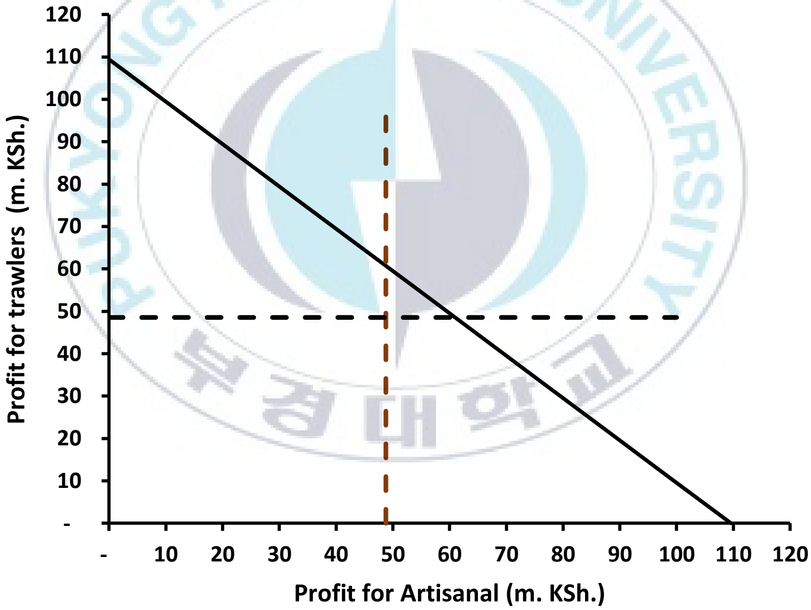

Figure 5: Profits obtained in cooperative solutions to the game (diagonal line), and profits obtained by each fleet in the non-cooperative solution. The latter define each fleet's threat point.

The threat point profits are at KSh. 48.6 million for the trawler fleet and KSh. 48.8 for the artisanal fleet. These threat points for the various agents correspond to catches of 227.9 t for the trawler fleet and 228.4 t for the artisanal fleet which are approximately 57% of the total annual catch for the fleets for the period considered in this simulation. Further, in this non-cooperative case the fleets maximize their profit with efforts of 171,889 boat-days and 688 trawler-days respectively.

Table 6: Efficiency ratios of fleets for different strategies.

Management Strategy	**Fleet**		
	Trawler Fleet		
	Profit/ catch (KSh/ kg)	**Profit/ effort (KSh/trawler-day**	**Catch/ effort (kg/trawler-day)**
Cooperation	271	105,871	390
Non-Cooperation	213	70,554	331
	Artisanal Fleet		
	Profit/ catch (KSh/ kg)	**Profit/ effort (KSh/ boat-day)**	**Catch/ effort (KSh/ boat-day)**
Cooperation	272	425	1.56
Non-Cooperation	214	283	1.33

Table 6 shows the efficiency ratios for the two fleets under cooperation and non-cooperation. Comparisons are made of the profits per unit of catch, profits per unit of effort and catch per unit of effort for the two fleets.

6 Discussion and Recommendations

6.1 Status of the fishery before the ban

The MSY obtained in this study is similar to those obtained by other researchers that have studied the same fishery before. According to Fulanda et al. (2011), who applied the Gordon (1954) model and the Gulland- Fox (1975) model in studying the fishery, the MSY for the prawn fishery is estimated at between 392 t to 446 t corresponding to a fishing effort (Emsy) of either between 7 and 9 trawlers or between 626,000 and 1,000,000 boat days. Ochiewo (2006) applied the Gordon-Schaefer (1954) model and estimated the MSY of the prawn fishery at 448 t, recommending a trawler effort (Emsy) of a maximum of 5 trawlers.

A comparison of the biomass estimates and the estimated MSY of the prawn fishery with catches over the 21 year history shows that the MSY of the fishery has been exceeded only on two occasions. First in 1998 when the total catch was 616 t and again in 2001 when the total catch was 701 t.

Previous work on this fishery has reported that, based on declining catches over the years, it is overfished (Fulanda et al., 2011; SWIOFC, 2012; Shelton, 2014; KMFRI, 2017) . It is however important to appreciate that declines in catches in the fleets should also be attributed to the fleet interactions among other factors and not just to biological overfishing per se. This is presupposed by the fact that the drop in catches in the years where they are reported as low does not necessarily correspond with high effort in the fishery. Biological overfishing, tends to occur when there is a marked steady drop in catches that corresponds to increase in effort.

There could be two main reasons behind the drop in catches and CPUE in the trawler fleet before their ban. The first is the exit of trawler vessels solely motivated by escalation of conflicts and the second is that most prawns are found under the 3nm zone and thus under the circumstance of escalated conflicts over access of the inshore fishing areas, it is possible that catches of the trawl fleets declined due to their inability to access these inshore areas. Further investigations are needed to also understand and document the contribution of environmental aspects such as the adverse weather phenomenon such as the El-Nino occurrence as well as the influence of fluctuating water quality (sediments load) on the prawn stocks in the bay.

Based on this study’s outcomes, the historical exploitation of the fishery and possibly the present exploitation levels are within the sustainable levels of the fishery, this does not however mean that the fishery is at its most optimum point given other factors that might be at play such as the ratio of catch to discards problems, lack of effectiveness of the artisanal fleet and such.

Catch trends presented in Figure 2 indicate the existence of a moderate negative correlation between the trawler catches and the artisanal catches over the period 1985- 2005. This indicates evidence of important interactions among the fleets over the prawn fishery. The catches of the artisanal fleet greatly depend upon the trends in catches of the trawler fleet, increasing to a significant extent with decrease in trawl catches and vice versa.

The period before the ban is characterised by a large amount of undisclosed bycatch among the two fleets and excessive discards especially in the trawler fleets. These are placed at a ratio of between 1:1.5 and 1:1.7 over period prior to the ban (Fulanda et al., 2011; Munga et al., 2012). Generally, in the East African coast, discards are placed at about 76% of the catch from the various prawn fisheries (Silas, 2016). The amount of bycatch retained for economic use among the fleets increases in the period just before the ban (Munga et al., 2012). According to Mwatha (2002), over 25% of the discarded fish in the bottom trawl fishery comprised of various juvenile species targeted by the artisanal fleet thus pitting up conflicts with the artisanal fleets.

It is noteworthy that in the Ungwana Bay scenario due to the dwindling prawn catches, the bycatch from the fishery is landed and considered as an important supplement and source of alternate income for the fleets (Fulanda et al., 2011).

The status of the fishery is analogous to the description of Warui (2014) of an unmanaged competitive fishery in its development stage where as the fishery matures, effort increases and could make the fishery suboptimal.

6.2 Game theoretic outcome

6.2.1 The non-cooperative game

In the non-cooperative scenario, each fleet adjusts their effort in response to the other's effort level in order to maximize its own profits. In the model, this scenario results in exploitation of the fishery such that the artisanal vessels are able to catch just more than half the available catch. This is suboptimal since the total profits obtained by both fleets in non-cooperation are lesser than those obtained with cooperation. The total catch in non-cooperation is higher at 456 t than the total catch for any share regime of cooperation indicating non-optimality and rent drain given that higher profits can be obtained from a lower total catch under cooperation.

The amount of profit per unit of catch, profit per unit of effort and catch per unit of effort for the fleets is lower in the non-cooperative scenario indicating inefficiency in terms of these ratios compared to the cooperative strategy.

6.2.2 The cooperative game

In this model, assuming the absence of side payments, the fleets would be willing to cooperate at an allocation of total profit in the fishery when the catches are allocated at 50 % to the respective fleets. This is the Pareto optimal allocation and is where the allocation yields cumulative profits larger than those for non-cooperation of the fleets. Following the estimated biomass in the model, both fleets would obtain undiscounted profits of about KSh. 54.8 million for the artisanal fleet and KSh. 54.7 million for the trawler fleet. These profits are obtained from a total catch of about 403 t.

For both fleets, there are higher profits per annum for cooperation than there are for non-cooperation. These profits are also at lower levels of catch and effort than for non-cooperation suggesting that cooperation in this case increases the efficiency and profitability of the fleets. There is potential for benefits in cooperation and sharing of the prawn resource subject to the management of the fishery regulating the fishing effort to optimal (MEY) sustainable levels.

Given that comparatively higher profits are obtained at lower catch and effort levels in this scenario is indicative that it is much more effective and efficient than the non-cooperative strategy.

Cooperation of fleets not only increases their profitability but also increases the effectiveness of their effort and has ultimate overall benefits of optimality of the fishery.

6.3 The optimal fishery

A fisheries management regime is considered optimal when among other outputs, there are maximum sustainable benefits from the resource itself (Warui, 2014). Efficiency in any economic management of a fishery further ensures that there are no rent drains from the resource. Biological sustainability and economic viability are the key attributes of the management objective presented in the prawn fisheries management plan used as the management instrument in this fishery (Government of Kenya, 2011). Optimality in this fishery should therefore focus on strategies for profits or rents maximization of fishers, reduction in rent drain, provision of the requisite circumstances and environment for an efficient fishery while ensuring that the biomass is exploited sustainably.

Historical efforts and catches from the Ungwana Bay prawn fishery have not been optimal. Until the time of the ban of the trawl fishery, effort levels in both fleets were high with profitability and efficiency low. From the results above, it is evident that the Malindi Ungwana Bay prawn fishery is still not at its optimum level. There is certainly inefficiency and large rent drain given the fact that there is no focus in understanding and considering the interactions of the fishers in its exploitation.

The artisanal fleet in this study are presented as marginally more profitable than the trawler fleet. Realistically this might be different given their mixed species fishery nature, diverse objectives for fishing, gear diversity as well as the presence of migrant fishers which are some of the complexities that can hinder the development of a profitable artisanal fleet. Optimisation of profits in a multi-species fishery often leads to over-exploitation or under-utilization (Fulanda et al., 2011).

The semi-industrial trawl fleet has the capacity and the features of the fleet that could be the more effective of the two given that it predominantly targets prawn catches; fishes in the offshore waters where there are adult prawns; targets the export market that can often have better prices; is comprised of few vessels that could be easy to manage among other suitable attributes. Given these, a management strategy of the fishery that allocates the trawl fleet more catch with side payments to the artisanal fleets could be workable and effective.

The MEY of the fishery is only effectively exploited by 4 or at most 5 trawler vessels. This is within the regulation of the prawn fishery management plan that limits the number of trawlers beyond the 3 nm to only 4 vessels each with a maximum of 300

GRHP (Government of Kenya, 2011). This limit on the number of trawler vessels should be enforced and adhered to until sufficient stock assessments and scientific evidence justify any increase in the number of vessels.

The management of the fishery should move from simple input controls to much more direct management of the fleets. These would include direct measures such as various fishing gear restrictions, stricter bycatch mitigation mechanisms, fishing effort controls, reference points and indicators, enforceable harvest control rules and strategies, decision control rules, fishing and harvest rights and limits on target species and bycatch species as well as detailed time and area restrictions. Considerations on the interactions between various target species and the fishers in the fishery should be incorporated. The impacts of trawling on the habitat and prawn as well as other target species need also be factored in any optimal management strategy.

Many developed countries adopt property rights-based fisheries management given that it promotes responsible resource stewardship and is usually associated with maximized economic rents (Arnason, 2015). Property rights-based regimes are efficient in addressing the issues related to open access and unregulated fishing effort. They are ideal as incentives for fishers to act rationally and sensible for the benefit of all users of the fishery.

The Ungwana Bay fishery is characterised by the presence of a resident and migrant artisanal fishery that is largely lightly regulated and is chaotic typical of an open access fishery. There is therefore a strong need to explore a property rights-based management system in the fishery. The property rights could be in the form of community based fisheries rights or individual transferable quotas. Communal rights system could be weaved about a comanagement framework and especially among the small-scale artisanal fishers as recommended by Fulanda et. al., (2011) for the Ungwana Bay fishery. Individual harvest quotas can alternatively be allocated to the artisanal vessels via the Beach Management Units that manage the fishery while trawlers could have their quota system managed by the State Department of Fisheries. This would be similar to the case of Mexico and Mozambique that use a quota system as one of the instruments to manage their prawn fisheries which feature large artisanal and commercial trawl fleets that have had histories of conflicts of interest between fleets in their respective prawn fisheries (Banks and Macfayden, 2011). Allocation of quotas for the fishery would lead to efficiency in the fleets and order in the artisanal fleet (Warui, 2014).

Based on the game theoretic analysis, the optimal management strategy of the prawn fishery should also include management of the interactions between the two fleets exploiting the resource. A cooperative mode between the two fleets would be more efficient and would have better profit maximization than the non-cooperative management. Besides better rents or profits, a cooperative strategy would also ensure better stock levels and sustainability given that it yields better profits from lesser catch than the non-cooperative strategy. A typical strategy in this case acknowledges the objectives, characteristics and efficiencies of either of the fleets and partitions the resource equitably ensuring that each fleet is granted responsible access to the resource in a manner that is economically efficient to the particular fleet.

Discards in the fishery are also contributors of conflict in the fishery. Generally, the Ungwana prawn fishery produces excessive bycatch and discards which is usually used for commercial and food purposes among the fisher community (Fulanda et al., 2011; Munga et al., 2012) Nevertheless, effective policy should be put into place to reduce bycatch levels, ensure better economic use of any allowed amounts of bycatch and reduce the amounts of discards as much as possible to that within sustainable levels for the fishery.

There hasn’t been adequate development of the artisanal prawn fishery to efficiently and effectively exploit the prawn resource in the bay. There is therefore a need to do capacity building of the artisanal fishers that would enhance their capacity to acquire proper and improved gear types, access more offshore areas and fish more effectively. Further, artisanal fishers should be educated on the use of simple technologies such as gear markers that would help reduce the conflicts over gear destruction by the trawler vessels.

Given the wealth of new knowledge on this fishery in the recent past and particularly after the lifting of the trawling ban on the fishery, it is imperative that a comprehensive revision of the prawn fishery management plan be undertaken to develop it further and turn it into an effective and useful tool for the optimal management of the fishery. The same should be an instrument based on an ecosystem approach to fisheries management rather than a precautionary approach given that sufficient biological, physical, economic and social information about the fishery is now readily available from this work among many others that describe the various aspects and status of the fishery.

Lastly, there is a need to provide sufficient monitoring, control and surveillance resources or mechanisms that would curb basic infringements, lawlessness and irresponsible fisher behaviour that typically escalates conflicts among the various users.

6.4 Limitations of the study

i) The Malindi Ungwana Prawn fishery has undergone about two significant changes in fishing regimes since the period from which biomass estimates were made for this study. The first period is during the trawling ban between 2006 and 2012, while the second one is the period after the reopening of the trawling up to the current period. These changes coupled with other environmental dynamics have the capacity to affect biomass dynamics in the fishery. Simulations of this model using actual current biomass figures can address the variations that could be as a result of the evolution of the biomass during these times.

ii) The simulations in this work have been based on estimates computed from secondary data. These then introduces the likelihood of data errors and a possible array of errors related to estimation and computations. It is important that any management strategies based on the model and methodology discussed in this paper be based on actual and recent data from the fishery.

iii) The model is largely static and deterministic, not taking in to consideration the dynamics of time and the presence of various uncertainties.

iv) The parameters and performance of the two fleets depend on a number of factors such as the abundance and availability of different species, weather and climatic factors, the dynamics of the fish markets among other factors. These have implications on the profitability of the fleets.

7 Conclusion

This study attempted to understand the status of the prawn fishery and the interactions among the players with the objective of analysing the problem, estimating benefits from possible scenarios and suggesting an optimal strategy for managing the resource.

Evidently, important and very key interactions exist between the fleets exploiting this fishery. Optimal management of this fishery should begin with acknowledgement of these interactions and formulating of strategies and policies thereof that provide for the fishing fleets to cooperate and be equally responsible in the exploitation of the resource.

This optimal management strategy should include the revision and review of the existing prawn fishery management plan and other related legislated management measures applied in the fishery. This should then be followed by provisions for enforceable incentives that allow for co-ownership and co-management of the shared prawn resource.

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