A Bioeconomic analysis of Maldivian Skipjack Tuna Fishery

Master thesis in International Fisheries Management

(30 Credits)

By

Solah Mohamed

Department of Economics and Management
Norwegian College of Fishery Science
University of Tromsø

May 2007

ABSTRACT

Skipjack tuna fishery in the Maldives is the most important and by far the predominant fishery in the country. This fishery is an open access fishery and has been developing over the years. With the technological development fishers have been moving further in search of fish and catch has been increasing steadily.

No stock assessment of the exploited tuna stock has been undertaken. Effort data from the Maldivian skipjack tuna fishery from 1985 to 2005 is standardised to a standard year 2005 vessel and standardised effort has together with catch data been used to calculate the parameter values for the Schafer and Fox surplus production models. The parameterised models are used to estimate the reference equilibriums of open access, maximum sustainable yield, maximum economic yield and the solution of social optimum. The analysis indicates that present level of effort in the fishery is close to the level of maximum sustainable yield (of about 100 thousand tonnes), but increase in cost and uncertainties related to recent changes in fishing pattern may show this situation to be unsustainable and cause a reduction in fishing effort under open access. This analysis also suggests that with current cost and price, this fishery may not be biologically overfished.

Keywords: Maldivian Fisheries, Skipjack tuna fisheries, Fisheries Bioeconomics, West Indian Ocean Tuna Fishery

ACKNOWLEDGEMENT

Tusen Takk to the Norwegian Centre for International Cooperation in Higher Education (SIU). If not for the NORAD scholarship my dream of studying in Norway would never become a reality.

My sincere gratitude goes to my supervisor Associate Professor Arne Eide. His guidance and advice was unprecedented from the very beginning till the very end. I could not have asked for more. Thank you indeed.

Thanks to all the lecturers and tutors who generously shared their knowledge and kept up with us.

It is a pleasure to meeting my IFM class mates. In spite of our differences we have became a close bunch of friends. I'm going to miss my wonderful classmates.

My wife is the one who persuaded me to apply for this scholarship. Throughout the course, more than anyone else, she has been supportive and encouraging. I thank my wife for believing in me and standing behind me in every challenge I aspire in my life.

There is a never ending list of people I want to thank for helping me to complete this journey. For all those who contributed (even in a small way) to the success of my study in Tromsø, I say thank you very much.

Solah MOHAMED

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1. INTRODUCTION

Skipjack tuna fishery in Maldives contributes around 70% of total landings and is the most important fishery in the country. This is an open access fishery; there is no entry or landing restrictions for locals.

Over the years this fishery has been developing steadily and catch has been increasing. With technological developments, fishers also have been increasing their area searching for fish. However still most of this fishery takes place within 75 miles of shore line. Unlike other skipjack tuna fisheries around the world, Maldivian fishers exclusively use pole and line (bait boat) for skipjack tuna fishing. Purse seining and gill netting is not permitted in Maldivian EEZ. Foreign and joint-venture long liners are permitted under licence in outer waters of EEZ (75 – 200 miles); the inner waters (up to 75 miles from the shore) are reserved for local fishers.

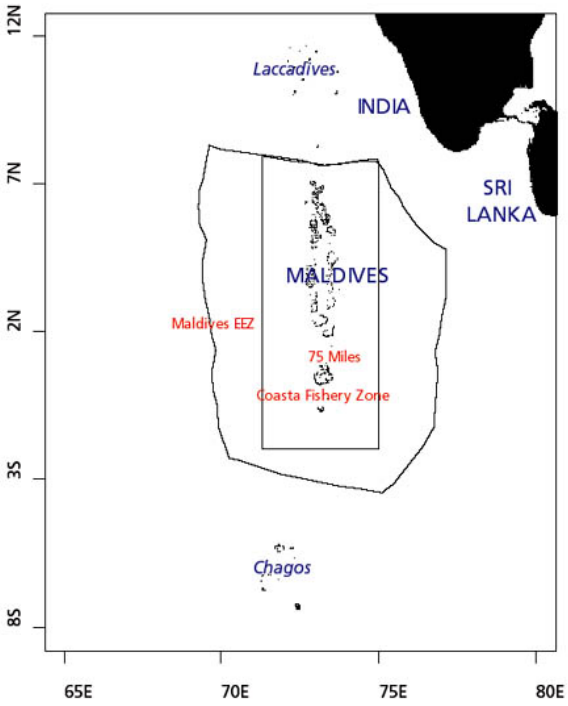

Figure 1: Maldivian EEZ and 75 mile reserved for local fishers (Shiham Adam, 2004)

There is no known stock assessment for the skipjack tuna stock in Maldivian waters. It is not yet clear if this is an exclusive stock to Maldives or an integrated stock with rest of the Indian Ocean. Tagging experiments carried in Maldives in 90s indicated that there is very little migration from Maldivian water to rest of the Indian Ocean (Shiham Adam & Sibert, 2002). Also no stock assessment is available for the Indian Ocean skipjack tuna stock. Given the characteristics of skipjack tuna and as they appear to be less migratory than other species of tuna, the last report of the Indian Ocean Tuna Commission (IOTC) acknowledged that smaller management units for skipjack could be possible (IOTC, 2006b). Hence in this analysis skipjack tuna stock in Maldivian waters is considered exclusive to Maldivian fishers.

Increasing cost of fishing effort may be the biggest problem to face for Maldivian fishers in the future. Increasing fuel prices may force the fleet to cut down the effort and many may have to leave the fishery. Also increase in other costs may cause a difficult situation and less ability to compete in the world market.

This analysis is an attempt to figure out the current situation in the Maldivian skipjack tuna fishery and to predict the trend in this fishery. Surplus production models of Schaefer (Schaefer, 1954) and Fox (Fox, 1970) were use to estimate the management reference point for Maldivian skipjack tuna fishery. For this type of fisheries other analyses methods may be preferable, but impossible given the data available.

Second section of this thesis gives some background information for the study, starting with brief information about the biology of this species and then followed by an overview of the Skipjack tuna fishery in the West Indian Ocean. This section then continues with a description of the Maldivian skipjack tuna fishery in particular. The last part of this section focuses market forces in this fishery.

The third section introduces bioeconomic modelling. Surplus production models by Schaefer (Schaefer, 1954) and Fox (Fox, 1970) are used in the analyses. Second part of the section presents equations representing economic reference points.

Fourth section is about the data and parameter estimation. Effort data of 21 years is standardised by a standard vessel of base year 2000. Parameters for the models are estimated using the regression methods used by Schaefer and Fox. Economic parameters are then calculated based on 2005 prices.

Fourth section presents the results of the analysis followed by the discussion and conclusion in the fifth section.

2. BACKGROUND

2.1. Biology of Skipjack tuna

Skipjack tuna (*Katsuwonas pelamis*) is a medium size perciform pelagic fish belonging to *scombridae* family. This species is found in the tropical and subtropical waters of all three major oceans of the world (Pacific, Atlantic and Indian Ocean). Skipjack tuna form large schools in surface with birds, drifting objects, dolphins, sharks and whales. Skipjack is also often found mixed with Yellowfin and Bigeye tuna of similar size (Collette & Nauen, 1983).

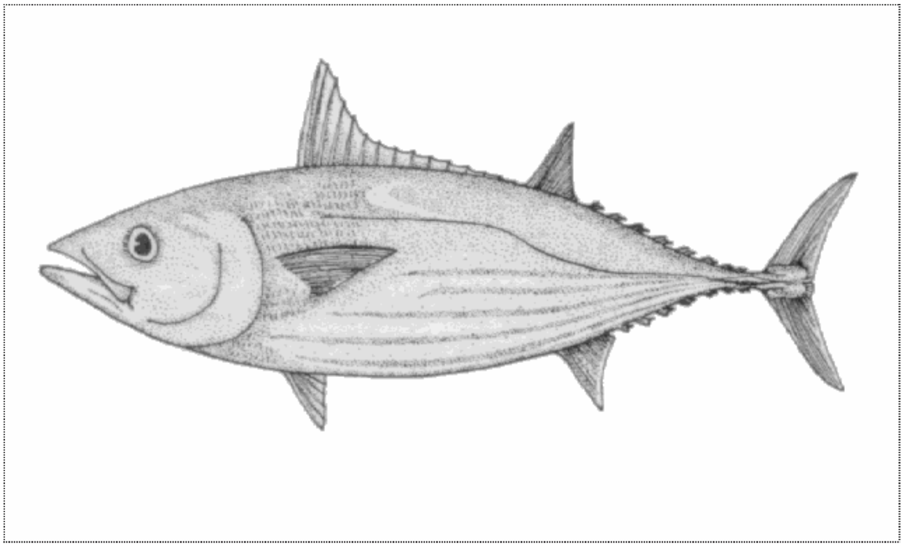

Figure 2: Skipjack Tuna (*Kalhubila mas* in Maldivian language). Illustration source: (Coad, 1995), www.fishbase.org

Skipjack tuna has high productivity compared to other tuna species. This species has a high fecundity and short life span, probably only up to five years (IOTC, 2006b). High turnover rate make this species more resilient to high fishing pressure compared to other tuna species. It spawns opportunistically through out the year in equatorial waters when the conditions are favourable. Although adult distribution of skipjack tuna may be in the temperature range 15-30˚C, larvae only survives at surface temperatures at 25˚C or higher (Collette & Nauen, 1983).

Skipjack tuna mainly feed on small fish, crustaceans and molluscs. The principal predators of skipjack are other tunas and billfishes. Average maximum size of skipjack tuna is about 80 cm in fork length and maximum weight is 8 – 10kg.

2.2. Skipjack tuna fishery in West Indian Ocean

Until 1980 more than 80% of skipjack tuna caught from West Indian Ocean (WIO) were caught by Maldivian bait boats, yet they fish within 75 miles of their shore line. Rest of the skipjack tuna catch during this time were mainly by Sri Lankan and Indonesian fishers. Before 1980 skipjack tuna catch from WIO were below 400 000 tonnes, from 1960 to 1980 catch was fluctuating between 100 000 and 400 000 tonnes. During this time target species for other main fishing nations (Japan, Taiwan and Indonesia) in the West Indian Ocean were bigger species of tuna[1] such as yellowfin, bigeye and albacore. Long line was used for larger species of tunas.

French and Spanish purse seiners arrived in WIO in the early 80s, targeting skipjack tuna for the canning industry. After their arrival catch increased rapidly, within a period of five years more than 50% of skipjack tuna catch was taken by the EU purse seining fleet. By mid 90s skipjack catch from WIO reached 260 000, out of which 160 000 was caught by purse seiners. The target market for skipjack tuna, canning industry, was unable to keep up with the rapid increase in the catch. As a result the market collapsed towards late 90s. There was a decrease in catch for a couple of years in the mid 90s, before it started growing rapidly again. In 2005 skipjack tuna catch in WIO reached 390 000 tonnes, which up to date is the highest recorded annual catch of the fishery (IOTC, 2006a).

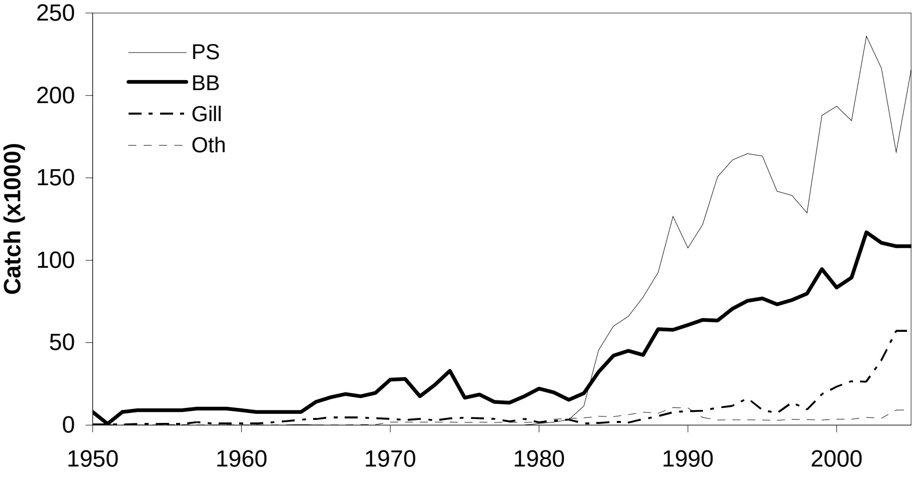

Figure 3: Catch trend in West Indian Ocean by major gear groups 1950 - 2005. PS= Purse Seine, BB= Bait Boats, Gill= Gill Net, Oth= Other of gears such as line and long line. Purse seine fleets are mainly by France and Spain. Bait boats are almost exclusively from Maldives. Data source Indian Ocean Tuna Commission (IOTC, 2006a).

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[1] There are no bluefin tuna in Indian Ocean.

Maldivian catches has also increased gradually since 1980 due to increasing fishing power (bigger boats with larger engines) and also due to use of fish aggregating devices (FADs). In the last 10 years Maldivian bait boats contributed for about 30% of the catch in the WIO, but still Maldivian fishers stay within 75 miles of their shore line.

2.3. Maldivian Tuna fishery

Historically Maldivian fisheries were almost exclusively based on the skipjack tuna fishery. Smoked and dried skipjack tuna, commonly known as *Maldive Fish* sold to Sri Lanka, used to be the principle source of foreign currency to Maldives. Over the years new types of fisheries were introduced and establish, but still skipjack tuna fishery is the most important and by far predominant fishery in Maldives.

Before 70s there were not many forms of processing the fish. Basically there were two types of end products; traditional smoked and dried tuna (*Maldive Fish*) and Slated and Dried fish. Only tuna species were used to make Maldive Fish. For salting, sharks and reef fish were the favourites, but tuna species are also salted in good fishing seasons.

In 1970 Sri Lanka cut back its import of Maldive Fish. In order to find an alternative for the foreign currency, government of Maldives invited foreign companies to Maldives to buy fish from fishermen, and Japanese Marubeni Cooperation became the first foreign company to start purchasing fish from Maldivian fishermen (Anon, 2003).

The mechanisations of Maldivian fishing boats started in the mid 70s. This allowed fishers to increase the area searching for fish and catch operation. As local fish catch increased, the need for product diversification and enhancing value addition resulted in setup of a Maldivian-Japanese joint venture canning plant in 1978 in the island of Felivaru.

Due to price fluctuations in the tuna market in late 70s and early 80s, foreign companies in Maldivian fisheries industry started leaving in early 80s. When Japanese investors ceased their operation in the Felivaru canning factory, government purchased the canning factory and later upgraded from 8 tonnes canning capacity to 50 tonnes canning capacity and a new factory was opened in 1986 (Anon, 2003).

In April 1983 State Trading Organisation (STO) of Maldives took over the fish purchasing operations from the last remaining Japanese company in the Maldives. After the Japanese companies relinquished their fish purchasing and caning operations in Maldives, government purchased the facilities used for their operations. From then on fish purchasing, freezing and canning operations were carried out by government companies, though under different names in different periods of time.

2.4. Last 20 years of the Industry

The following years after Japanese companies left Maldives, skipjack tuna fishery industry kept on growing steadily. While processing and export of *Maldive Fish* is open to all, export of frozen and canned tuna was controlled and monopolised by the government until recently.

Fisheries Projects Implementation Department (FPID), under STO, was established in 1986. This company took over the canning operation in the upgraded canning factory at Felivaru. They also took over the rest of the fish purchasing and freezing operations in the country, which included number of fish collecting and freezing vessels. During the time of FPID government invested on two fish collecting and freezing centres at the south of the country. In 1990 a high profile corruption case emerged in FPID, many in the top level staff of the company were removed from their posts and investigated for corruption. Government dismantled FPID and formed yet another company, Maldives Industrial Fisheries Company (MIFCO), to take over the operations of FPID, this time independent from STO.

With a single government company acting as the major force in the post harvest sector, effect of world market fluctuation on the local market was very little; fishermen had almost a fixed price for their catch in spite of ups and downs in the world market price. Even when the world tuna market collapsed in 1999/2000 the company was obliged to buy fish from fishermen. The government company also had a social responsibility to support the livelihood of the fishermen.

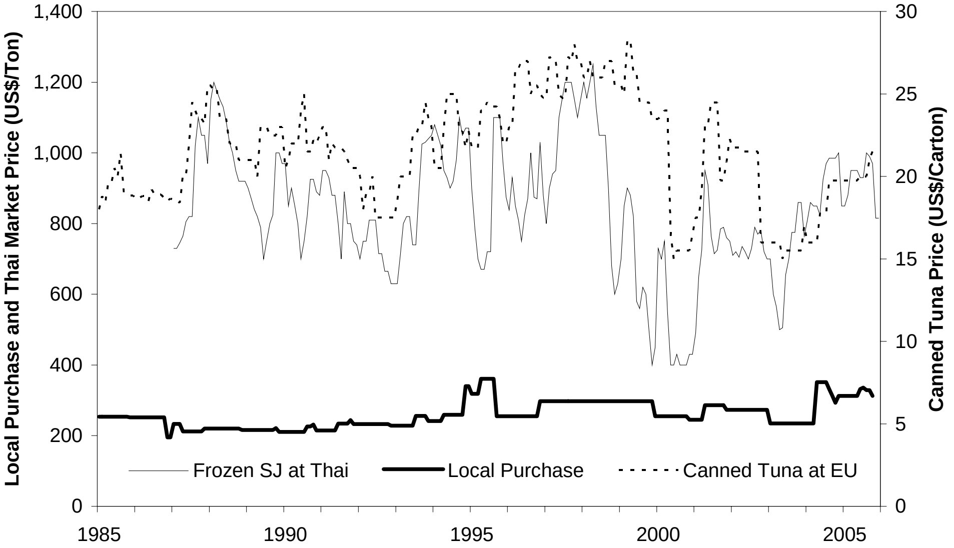

Figure 4: Price fluctuation in the main markets for Maldivian Skipjack tuna. Data source for Thailand and European market (Josupeit, 2006). Local purchase price data from (MPND, 2005a) and (MPND, 2005b). Local purchase price is converted to US$ using average exchange rate for the year.

With a stable purchase price and steady increase in the catch, harvest sector was encouraged to invest in larger boats; on the other hand with the uncertainty in the world market the post harvest sector was lagging behind. Some of the reasons that contributed to the lack of development in the post harvest sector could be;

1. Lack of incentives to invest enough in the sector: The government company is enjoying a monopoly situation and there was lot of uncertainty in the fluctuating world market.
2. Corruption inside the government fisheries company: During the time when canned tuna and frozen tuna price was at its highest, allegedly there was lot of corruption going on in the government fisheries company.
3. Social burden on the government fisheries company: In spite of the world market crash in 1999/2000, MIFCO was obliged to purchase fish from fishermen. Government lent money to MIFCO during the time of the crisis. This was also the time Maldives had the highest catches; harvest sector got money and reason to invest while MIFCO was dragged into debt as a result of borrowing money to pay fishermen.

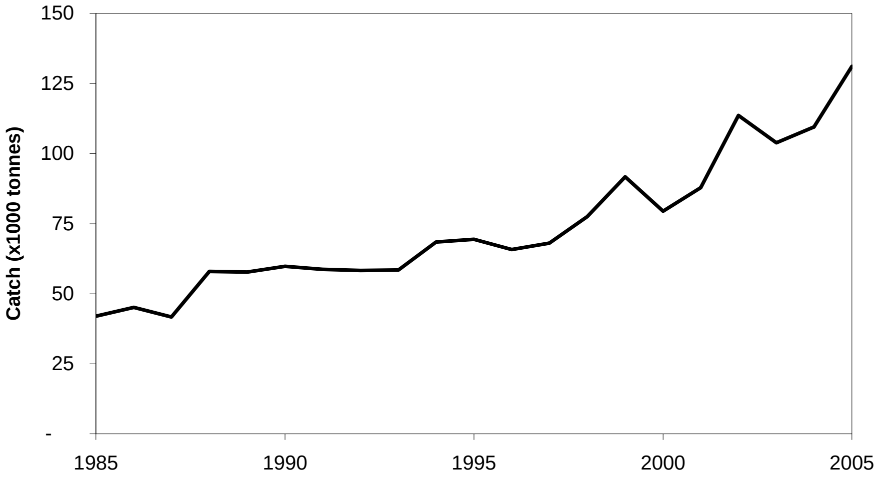

Figure 5: Development of Maldivian skipjack tuna fishery, 1985 – 2005.

In good fishing seasons it is common that the post harvest sector is not able to handle the harvest. Almost every year there will be a few weeks fishers have to throw away most of their catch. With the fast development of the fishing sector, the gap between harvest sector and post harvest sector kept on growing. As a result governments' policy to monopolise the post-harvest sector was heavily criticised. Increasing pressure led to the government seeking for solutions and finally deciding to ease the monopoly.

In 2003 the government invited private companies to join the export of frozen and canned tuna from the country. The sector is still not a complete open market, only few companies who won the bid to join the operation were allowed to enter the sector. Newly joined private companies has invested heavily to develop landing ports, cold storages, and processing facilities, while the government company, MIFCO is also investing to improve their operation and increase their capacity. It would take few more years before new companies start operating at their full capacity. In the mean time harvest sector is also continuing to grow.

2.5. Market forces in the Maldivian Skipjack tuna fishery

About 20-30% of the skipjack catch is consumed locally, the rest goes to export. Major forms of skipjack export are as frozen tuna, canned tuna and as Maldive Fish. Frozen tuna and canned tuna processing and export are by companies while Maldive Fish is processed in small scale cottage industry and sold to exporters, and exporters sell them to Sri Lankan market.

Purchasing prices by companies are somewhat stable while local consumer market price and auction market price for cottage industry fluctuates a lot. As the purchasing price of big companies is less elastic to supply, in periods of low catches big companies would be the last choice of the fishermen. When fishing is low fishers go to the island markets before delivering to collector vessels or collecting centres of the companies. At island markets they might choose to auction the whole catch or retail it. When catches are very low fishers choose to sell them on local market at higher price. In local consumer market it is common to reach a price of 1 US$ per kilo tuna when supply is low. Maldive Fish processors mainly get their raw material from auctions at island markets. Going price of these auctions depends on the supply and also Maldive Fish price at Sri Lankan market.

As government is easing the monopoly in the sector, competition between the companies are expected to make purchase price more elastic to supply and also to the fluctuations in the world market.

Major export market for Maldivian frozen skipjack tuna is Bangkok, while the European market is the most important for canned tuna. Having a very small share of the market, Maldives has no influence on these markets. In the Bangkok frozen tuna market Maldives is competing with countries like Taiwan, South Korea and Indonesia. In the European canned tuna market Maldives in competing with countries like Thailand, Spain and Philippines. High production costs due to lack of resources in the country gives the Maldives disadvantages in these markets. Low fishing costs (compared to other fishing methods such as purse seining) of pole and line fishing has enabled Maldivian stay in these markets. With increasing cost of effort, this advantage may soon disappear.

3. BIOECONOMIC MODEL

3.1. Biological Growth Models

3.1.1. Verhulst-Schafer Growth Model (Logistic Growth Model)[2]

Populations of organisms cannot grow infinitely, growth of organisms are constrained by environmental conditions and food availability. It has been shown that populations of organisms strive to stabilise at highest possible population size for a given set of conditions (Schaefer, 1954). Marginal growth of a population increases when the size of the population decreases, and marginal growth decreases when the size of the population increases, this may be called density dependent growth. Biological growth of such population may be expressed as

$$F(X) = rX + sX^2 \tag{1}$$

Where X is population size, r is the growth rate of the population and s is the mortality rate which is negative. This is a parabolic equation also referred to as Verhults' equation or the logistic growth equation (Schaefer, 1954).

When the population reach the environmental carrying capacity, K, growth and mortality of the population is equal, and rate of change of population size with respect to time (*dX/dt*) becomes zero. The mortality rate s can now be expressed in terms of r and K as

$$s = \frac{-r}{K} \tag{2}$$

Substituting s in equation (1) by equation (2) we get the most commonly used expression of the logistic growth equation.

$$F(X) = rX\left(1 - \frac{X}{K}\right) \tag{3}$$

Harvest is just another type of mortality. With the introduction of harvest, the rate of population change (*dX/dt*) is;

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[2] P. F Verhulst first introduced the logistic growth function in 1883, but it became popular when R. Pearl and L. J. Reed rediscovered it and used it in an empirical work, employing statistics from US population in 1920.

$$\frac{dX}{dt} = F(X) - H(E, X) \tag{4}$$

where

$F(X)$ = Natural annual net growth of the stock

$H(E, X)$ = Annual harvest as a function of fishing effort (E) and stock size (X).

In the absence of harvest, rate of change of population size (dX/dt) equals the biological growth rate of the population, $F(X)$.

Annual rate of renewal of a fish stock depends on three major factors; biological environment, physical environment, and magnitude of the remaining population. Biological environment and physical environment may be considered to be constant in the long run (Schaefer, 1957). Population size is reduced by natural and fishing mortality. Harvesting increases the total mortality, consequently natural growth rate increases to balance the mortality. As the fish population strives to balance the total mortality with the growth, the population reaches a new equilibrium at a point where the growth rate equals total mortality, which occurs at a lower population size than the environmental carrying capacity level K. When the fish stock reaches equilibrium with a given effort level, all the biological growth of the population is harvested and there is no net change in the population size. Then

$$H(E, X) = F(X) \tag{5}$$

Assuming that each unit of effort harvest equal amounts from the targeted stock, harvest may be described by (Schaefer, 1954)

$$H(E, X) = qEX \tag{6}$$

where q is the catchability coefficient. Equation (6) implies that harvest (H) is proportional to the stock size (X) at a given fishing effort E. Assuming an equilibrium situation where catch equal natural growth, the equilibrium stock size (X) may be expressed in terms of K, q, E and r.

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

and when $X \neq 0$

$$X = K\left(1 - \frac{qE}{r}\right) \tag{7}$$

By substituting X in equation (6) by (7), we get the long term catch equation.

$$H(E) = qKE - \frac{q^2KE^2}{r} \tag{8}$$

This implies that although harvest is a function of effort and stock size for a short term, in a long run stock size becomes only a function of effort (given that environmental conditions are constant) and the sustainable yield too becomes a function of effort only.

Equation (8) takes the form of a parabolic equation, which allows us to use a linear regression in order to estimate the parameters of the function of sustainable harvest (*H*). Dividing both sides of equation (8) by effort (*E*) we get the linear equation of catch per unit of effort (CPUE).

$$CPUE = \frac{H}{E} = qK - \frac{q^2KE}{r} \tag{9}$$

3.1.2. Gompertz-Fox Growth Model

In 1970 W. W. Fox outlined an alternative surplus-yield model, assume Gompertz growth function, resulting in an exponential relationship between fishing effort and population size and asymmetrical harvest curves (Fox, 1970). Generalised form of the Gompertz curve can be represented as (Winsor, 1932),

$$F(X) = \mu X(\ln K - \ln X), \tag{10}$$

Assuming that biological growth of the subjected population follows the model suggested by Gompertz, and also assuming the fleet is homogenous and all vessels have the same fishing power.

$$F(X) = \mu X \ln\left(\frac{K}{X}\right) = qEX \Rightarrow X = Ke^{\frac{-qE}{\mu}} \tag{11}$$

By substituting X in equation (6) by (11) we get

$$H(E,X) = qEKe^{\frac{-qE}{\mu}} \tag{12}$$

Dividing both sides of the equation (12) by fishing effort (*E*) yields

$$CPUE = \frac{H}{E} = qKe^{\frac{-qE}{\mu}} \tag{13}$$

A log-linear expression is found by

$$\ln(CPUE) = \ln(qK) - \frac{q}{\mu}E \tag{14}$$

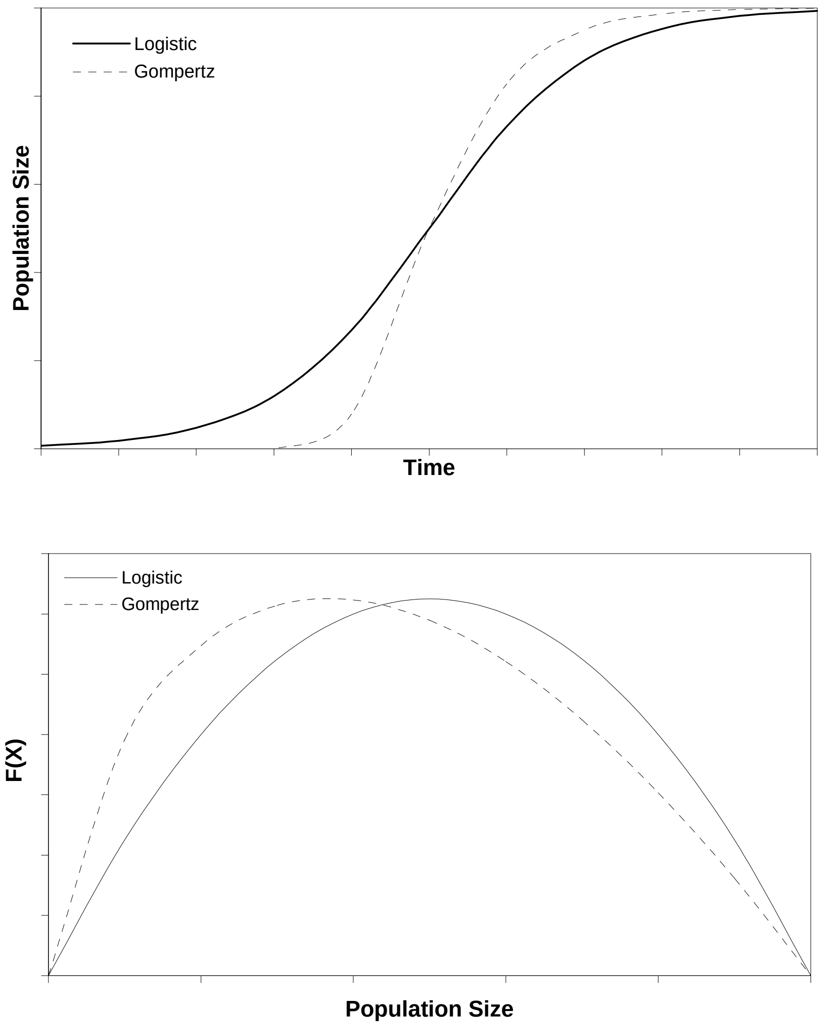

Figure 6: Illustrates the difference between Logistic and Gompertz population growth model.

The major difference between Logistic model and the Gompertz model is that at lower population size Gompertz model predicts a higher growth rate than logistic model. At higher population size logistic model predicts a higher growth rate than prediction by Gompertz model. In Logistic model maximum growth occurs at half of the maximum population level. In Gompertz model maximum growth occurs at population level less than the half of maximum population, around 37% of maximum population. In other words population growth curve of Gompertz model is skewed to left while population growth curve of logistic model is symmetrical. This is illustrated in the Figure 6.

3.2. Fisheries Economics

At any point in time, harvest is a function of fishing effort and size of the fish stock. For any given population size higher the effort, larger the harvest. At any given level of effort, the larger the population size is, the larger is the harvest (Anderson, 1986). As discussed earlier, when harvesting is introduced to a virgin fish stock, the size of the stock decreases and a new equilibrium stock level is reached at a level below the environmental carrying capacity level. Since the catch varies with the level of effort a different equilibrium population will result at each level of effort. And as shown in the previous section long term stock size and sustainable yield becomes only a function of effort.

In fisheries economics input is *Fishing Effort* which may be considered as an intermediate product that requires input of labour capital and investment. If c is the unit cost for each unit of effort[3] (E), the total cost in the fishery may be defined as

$$TC(E) = cE \tag{15}$$

And assuming a constant price for all the harvest, the total revenue from the fishery would be unit price (p) multiplied by the total harvest (H).

$$TR(E) = pH(E) \tag{16}$$

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[3] Fishing effort may be measured in different units. The unit of choice is based on the type of fishery. For trawling, time trawled may be used, for pot or gillnet soak time may be the best unit to measure the effort. But in most of the cases number of fishing trips may be the only available measure of effort.

While assuming the unit cost of effort (*c*) also to include opportunity costs, the revenue exceeding what is need to cover the cost *TC*, is the *resource rent* (*π*):

$$\pi(E) = TR(E) - TC(E) \tag{17}$$

3.2.1. Open Access Equilibrium (OAE)

If the fishery follows basic economic laws, fishers would continue to enter the fishery until there is no supernormal profit (resource rent, in fisheries terms) to earn from the fishery. In other words fishers would continue enter the fishery until their average revenue levels with their marginal cost of effort. Assuming fishing homogenous fleet and all input factors have the same opportunity costs, the situation of open access may be defined as follows in equilibrium

$$\frac{TR(E)}{E} - TC'(E) = 0 \Rightarrow \frac{TR(E)}{E} = TC'(E) \Rightarrow p\frac{H(E)}{E} = c \tag{18}$$

Substituting the harvest equations (Equation (8) for Schaefer model, equation (12) for Fox model) for harvest, (*H*) in equation (18) and solving the equation to effort (*E*), we may find the effort level at which the fishery would stabilise if a fishery is unregulated.

Table 1: Formulae to calculate open access equilibrium effort level

Open Access Equilibrium: *AR = MC*	
Schaefer	$E_{OA} = \left(\frac{c}{p} - qK\right) \cdot \frac{r}{q^2 K}$
Fox	$E_{OA} = \left(\ln qK - \ln\left(\frac{c}{p}\right)\right) \cdot \frac{\mu}{q}$

3.2.2. Maximum sustainable Yield (MSY)

Maximum sustainable yield (MSY) is the largest yield that can be sustained for indefinite period of time. This occurs at the point where the natural annual net growth of the fish stock is maximised. For Schaefer model maximum growth exactly at half of the carrying capacity of the stock. For Fox model maximum growth occur at a population level less that half of carrying capacity.

Table 2: Formulae to calculate effort level that could achieve maximum sustainable yield

Maximum Sustainable Yield: *H'(E)=0*	
Schaefer	$E_{MSY} = \frac{r}{2q}$
Fox	$E_{MSY} = \frac{\mu}{q}$

3.2.3. Maximum Economic Yield (MEY)

Maximum Economic Yield (MEY) is the yield which would generate maximum resource rent from the fishery. Maximum Economic Yield (MEY) is obtained when the marginal cost of fishing effort are equal the marginal revenue from the fishery.

Table 3: Formulae to calculate effort level that could achieve maximum economic yield

Maximum Economic Yield: *MC(E)=MR(E)*	
Schaefer	$E_{MEY=} \frac{r(pqK - c)}{2pq^2K}$
Fox	$E_{MEY} = \frac{\mu}{q}\left(1 - \omega\left(\frac{ce}{pqK}\right)\right)$ ω = Lamberts function

3.2.4. Optimum Sustainable Yield

Optimum Sustainable Yield is the yield which would maximize the present value of the flow of resource rent from the fishery in all future. Leaving more fish in the sea is expected to cause a higher stock next year, hence reducing the cost of fishing one unit. The value of harvest also grows in the bank by the interest rate, while unharvested fish grows in value by biological growth and reduction in unit cost of harvest.

Resource owners' decision either investing the resource value in the best alternative placement (for example in a bank deposit) or investing in the fish stock, therefore also depends on the interest rate of the best alternative placement. Given an infinitely high interest rate it is better to deplete the stock and invest all the value rather than leaving valuable fish in the sea with limited growth. At low interest rates it is better to reduce effort towards the MEY equilibrium. The "Golden Rule" equilibrium of maximizing present value is given by (Clark, 1976);

$$p - c(X^*) = \frac{1}{\delta} \cdot \pi'(X^*)\,, \tag{19}$$

X^* representing the optimal equilibrium stock. By converting the variable to fishing effort, equation (19) may be represented by an alternative expression,

$$\frac{p \cdot H(E^*) - c \cdot E^*}{E^*} = -\frac{1}{\delta} \cdot \pi'(E^*)\,, \tag{20}$$

E^* representing the optimal equilibrium effort.

Table 4: Formulae to calculate reference points

Optimum Economic Yield: $p - c(E) = \frac{1}{\delta} \cdot \pi'(E)$	
Schaefer	$E^* = \dfrac{(1+\delta)\cdot(-c + pqK)}{(2+\delta)\cdot p \cdot \left(\dfrac{q^2 K}{r}\right)}$
Fox	$E^* = \dfrac{\mu}{q}\left(1 + \delta - \omega\left(\dfrac{ce^{1+\delta}(1+\delta)}{pqK}\right)\right)$ ω = Lamberts function

4. DATA AND PARAMETER ESTIMATION

Catch and effort data are from Statistical Yearbooks of Maldives (MPND, 2005a), (MPND, 2005b), (MPND, 2006). In the Statistical Yearbooks effort is given in number of fishing trips per year. Catch and effort data is given separately for mechanised bait boats, sailing (non-mechanised) bait boats, trolling, and rowing vessels. Catch by mechanised boats was so dominant for the time period data is available, that catch by other categories of vessels in this fishery in negligible. By 1990 there were hardly any non-mechanised bait boats in the skipjack tuna fishery. For trolling and rowing vessels, skipjack tuna is not a target species. Therefore only Skipjack catch and fishing trips made by the mechanised bait boats is used in the parameter estimations.

Although the large majority of mechanised boats are specialised in pole and line skipjack tuna fishing, there are several boats specialised for yellowfin tuna fishing in this category. Since the number of vessels engaged in yellowfin tuna fishery is not documented separately, fishing trips made by mechanised boats also includes trips targeting yellowfin tuna. As yellowfin and skipjack of similar sizes often form mixed schools catch by mechanised boats may be a mix of yellowfin and skipjack. National statistics shows in recent years about 70% of the catch by mechanised boats is skipjack, 12% is yellowfin and the rest is other tuna related species. (Catch compositions of mechanised boats are given in Appendix 1.)

Similar sizes of yellowfin and skipjack do not differ much in price. But the GG category of Yellowfin (Yellowfin above 12kg, instantly killed, bled, gutted, gilled and chilled on board) of good quality can get a much higher price than skipjack. Composition of other species in the mechanised bait boats catch becomes significant when calculating the revenue from the fishery, because they generate revenue and contribute to cover the cost. Although there are prices differences between species and markets, purchase price by the government company is the only available documented price in a time series. For this reasons in the parameter estimations it was assumed a constant price for the harvest of mechanised boats, which is the skipjack purchase price by companies.

4.1. Standardising Catch and Effort Data

Catch and effort data is aggregated for each year; catch in metric tonnes and effort in total number of fishing trips. Catch data was categorised by type of vessels and species.

Over the years technological developments has significantly changed the fishing power of the vessels. Also even in one year there could be significant difference in fishing power between vessels of different sizes. Therefore to compare the effort of different years and different sizes of vessels it is necessary standardise the effort to one standard vessel. To standardise the fishing effort 2005 is taken as the base year.

Engine power is a factor reflecting many components of the effort that potentially could change the efficiency. In general highly powered engines are used in bigger vessels. Following factors increase fishing efficiency of larger vessels with higher engine power.

1. Larger engines give higher speed, allowing them to cover larger areas searching for fish.
2. Bigger vessels can carry more bait and with larger bait wells bait stay alive for a longer period of time allowing bigger vessels to search larger areas without returning for more bait.
3. Bigger boats also have more people on board and use more poles to catch fish, enabling these vessels to load more fish in shorter time.
4. With bigger storage bigger vessels can carry more fish per trip.

Since the catch and effort data was not categorised by the size of vessel or engine power, average motor size in horsepower[4] has been calculated. To standardise the fishing trips for all the years, the percentage change in engine power has been used, 2005 being the base year.

In the second step of standardising effort, has to be scaled to a standard vessel of the year 2005. This is because all the prices and costs used in calculations are based on the year 2005.

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[4] Engine horsepower for fishing vessels are not available from any official publication. These averages are calculated from an unofficial registry data base recorded by the Ministry of Transport and Civil Aviation.

From the interviews with the vessel owners it was found that a standard vessel in 2005 catches an average of 1.5 tonnes per trip, which makes CPUE of a standard vessel higher than the actual average CPUE. Thus the effort level required to meet the catch of each year had to be scaled based on the standard vessel. Equation 21 is used to calculate the standard effort (E_i) for each year.

$$E_i = \left(\frac{HP_i}{HP_{2005}}\right)\cdot\left(\frac{FT_i}{FT_{2005}}\right)\cdot\left(\frac{H_{2005}}{1.5}\right) \tag{21}$$

Where

E_i = Standard Effort of year *i*

FT_i = Fishing Trips made in the year *i*

HP_i = Average engine horsepower of vessels in the year *i*

H_{2005} = Harvest in the year in the year 2005

Table 5 shows the calculated standard effort for the years.

Table 5: Catch, effort, average engine power, percentage change in engine power and standardised effort for the Maldivian Skipjack Tuna fishery: 1985-2005. Catch and number of fishing trips data are form (MPND, 2005a), (MPND, 2005b) and (MPND, 2006).

Year	Catch (MT)	Fishing Trips	Average Engine HP	% Change in Engine HP	Standard Effort (E_i)
1985	42,005	162,430	47	0.25	18,359
1986	45,099	161,910	52	0.27	20,335
1987	41,676	158,785	50	0.26	18,891
1988	57,966	184,353	47	0.24	20,644
1989	57,671	183,944	44	0.23	19,362
1990	59,724	193,045	47	0.24	21,558
1991	58,715	198,320	49	0.25	23,257
1992	58,269	204,808	52	0.27	25,595
1993	58,452	222,548	54	0.28	28,979
1994	68,453	223,095	61	0.32	32,461
1995	69,406	240,858	66	0.35	38,389
1996	65,794	239,789	72	0.38	41,486

Year	Catch (MT)	Fishing Trips	Average Engine HP	% Change in Engine HP	Standard Effort (E_i)
1997	68,066	237,661	81	0.42	46,136
1998	77,489	224,751	91	0.47	48,844
1999	91,721	210,816	105	0.55	53,260
2000	79,455	202,195	123	0.64	59,584
2001	87,847	205,897	141	0.73	69,391
2002	113,652	209,839	156	0.81	78,551
2003	103,864	208,471	164	0.85	82,008
2004	109,438	213,656	176	0.92	90,079
2005	131,121	189,941	192	1.00	87,414

4.2. Harvest parameter estimation

A linear regression of CPUE against standardised effort shows a declining trend of CPUE as the effort increases. A regression of CPUE and effort can be used to estimate the constants in the equation (9).

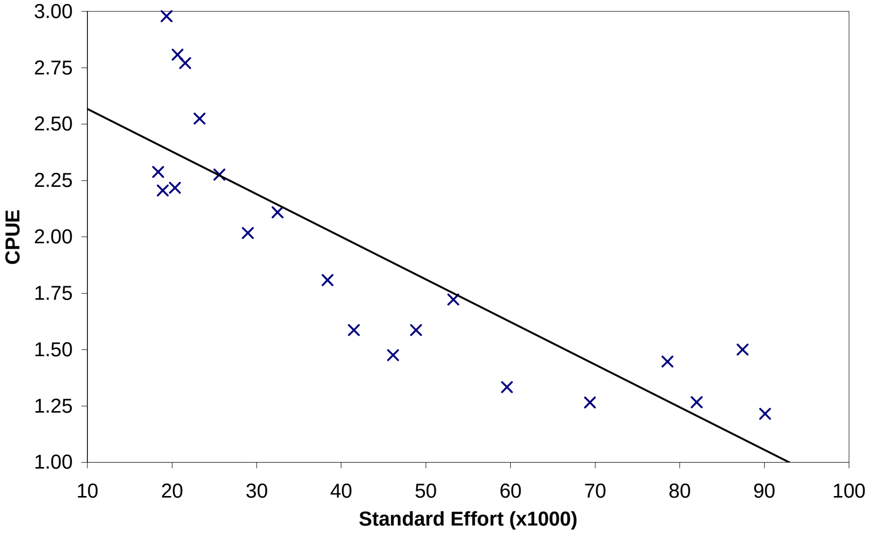

Figure 7: Regression plot of CPUE against standardised effort

From equation (9) CPUE may be expressed as a linear function of *E* with two parameters.

$$CPUE = qK - \frac{q^2 K}{r} E \Rightarrow CPUE = \alpha_1 + \alpha_2 E \qquad (22)$$

where $\alpha_1 = qK$ and is the intercept of the line, and $\alpha_2 = -q^2K/r$ and is the slope of the line. Estimated parameter values for the constants α_1 and α_2 were obtained by linear regression and are presented in Table 6.

Table 6: Parameters estimated for Schaefer model by linear regression using standardised effort and CPUE data from 1985-2005

Parameters	Coefficients	Standard Error	t Stat	P-value
Intercept (α_1)	2.75631948	0.133028	20.71977	1.67 E-14
Slope (α_2)	-1.8908 E-05	2.65 E-06	-7.14202	8.66 E-07
Adjusted R Square	0.71432024			

In the regression analysis adjusted R^2 of 0.7 indicates that 70% of the CPUE variation is explained by this model.

Similarly, a regression of ln(CPUE) against effort would give the values for constants in the Fox model.

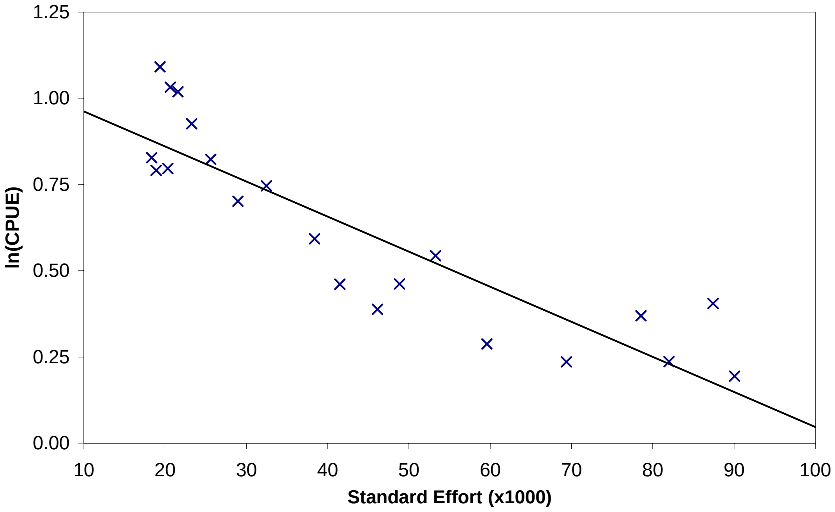

Figure 8: Regression plot of ln(CPUE) against standardised effort

Equation (14) can now be expressed as function of *E* with two parameters.

$$\ln(CPUE) = \ln(qK) - \frac{q}{\mu} E \Rightarrow \ln(CPUE) = \beta_1 + \beta_2 E \tag{23}$$

where $\beta_1 = \ln(qK)$ and $\beta_2 = -q/\mu$.

Since $\beta_1 = \ln(qK)$ and $qK = e^{\beta_1}$ equation (12) may be written as follows

$$H(E, X) = E.e^{(\beta_1 + \beta_2 E)} \tag{24}$$

Estimated parameter vales for β_1 and β_2 were obtained by log-linear regression and are presented in Table 7.

Table 7: Parameters estimated for Fox model by linear regression using standardised effort and ln(CPUE) data from 1985-2005

Parameters	Coefficients	Standard Error	t Stat	P-value
Intercept (β_1)	1.06352341	0.060879	17.46939	3.67 E-13
Slope (β_2)	-1.0169 E-05	1.21 E-06	-8.39382	8.15 E-08
Adjusted R Square	0.77642681			

In this model adjusted R^2 value of 0.77 indicates that 77% of the variation in the CPUE is explained by this model.

4.3. Economic parameters

Reference points for management are calculated on the basis of 2005 data. Towards the end of 2005 purchasing price of fisheries companies were fluctuating around Mrf 3.80 – Mrf 4.50 per kilogram of skipjack (corresponding to about US$ 300 – 350 per tonne)[5]. However, depending on the supply price at local consumer market and auction price in islands markets may be higher than companies' price. Since no documented data is available on consumer market price and auction price, in this analysis a unit price of harvest (*p*) is assumed to be US$ 350. And in the revenue calculation it was assumed that a standard vessel catches 1.5 tonnes per trip.

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[5] Exchange rate is Mrf12.80 = US$1

Major components of the unit cost of effort (c) in this fishery are fuel costs for the main engine, generator(s) and pumps. There is no fixed salary for fishermen in Maldives; they get their wage by part system. They share the profit and take the risk as well.

Fuel consumption for each trip (for each unit of effort) is calculated assuming the following.

1. Equation 25 gives the fuel consumption in L/hr for Yanmar marine engines horsepower above 70. (All most all fishing vessels in Skipjack tuna fishery have Yanmar Marine Engines. Formula to calculate the fuel consumption is provided by a senior engineer from the Authorised Yanmar engine distributor in Maldives. Yanmar Marine engines with horsepower below 70 are less fuel efficient so a different formula is required for engines blow 70)

$$Fuel\ Consumption = HP \cdot \frac{160}{840} \qquad (25)$$

2. Average engine horsepower of a vessel is assumed to be 190, which is the average engine horsepower for the base year, 2005.
3. Each fishing trip is set to 18 hours.

Through out 2005 fuel price was on the rise and at the end of the 2005, local price of litre of diesel is Mrf 7.65, which is about US$ 0.6 per litre (MPND, 2006). This fuel price and interviews with some boat owners are used to estimate the costs for the fishing trips. Although crew does not get a fixed salary there is opportunity cost of fishing for them. If the fishery is not making enough money, eventually fishers would exit the fishery. Thus crew wage is based on the basic minimum wage in Maldives and assuming an average of 20 crew members for each vessel.

Table 8: Components of cost of unit effort (c) in the Maldivian Skipjack tuna Fishery based on estimates of 2005 prices

Components	Cost (Mrf)/Trip	Cost (US$)/Trip
Fuel Cost	4,400	342
Crew Wage (For 20 Crew members)	1,600	125
Food Cost	250	19
Other Costs	200	16
Total	6,450	504

Table 8 shows cost estimates of different cost components and the unit cost of fishing effort. In the calculations of economic parameters unit cost of effort (*c*) is assumed to be US$ 500.

To estimate the OSY interest rate of 3% was assumed. This is based on the saving deposit rate by the commercial banks in the Maldives. OSY based on interest rate of 10% is also calculated to show what might happen in case of an increase in interest rate.

5. RESULTS

The figure 9 shows the harvest curves constructed for Schafer and Fox model using the calculated parameters for the Maldivian skipjack tuna fishery. Along with the harvest curves actual harvest from the historical catch data is also shown in the figure. This figure shows the consistency of the prediction based on the standard effort applied.

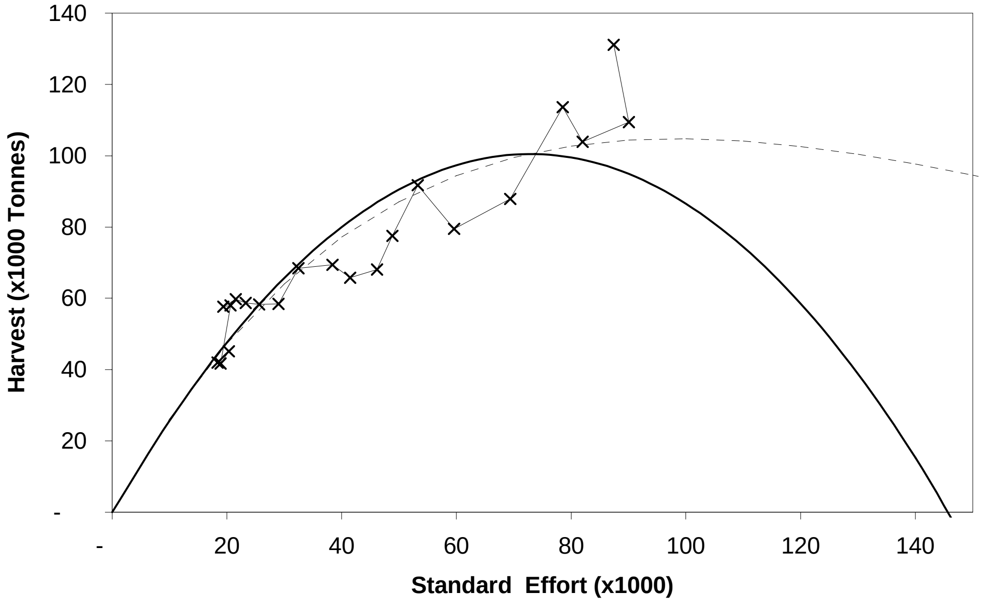

Figure 9: Harvest curves for Maldivian skipjack Tuna fishery for Schaefer and Fox model, along with actual harvest from 1985 to 2005.

Figure 9 shows that there is not much difference between MSY prediction by Schaefer model and Fox model. This is confirmed by the calculations presented in the table 9. This figure also indicates that in recent years catch levels are outside the sustainable levels.

5.1. Reference points

To calculate the reference points, equations were simplified by replacing the constants with α and β calculated by the regression analysis. Simplifications for all the reference points are shown in Appendix 2.

Table 9: Calculated reference points

Reference Points		Effort	Harvest
Maximum Economic Yield	Schaefer	35,112	73,469
	Fox	31,514	66,253
Optimum Sustainable Yield (δ =0.03)	Schaefer	35,631	74,205
	Fox	31,747	66,585
Optimum Sustainable Yield (δ =0.10)	Schaefer	36,631	75,805
	Fox	32,973	68,300
Open Access Equilibrium	Schaefer	70,223	100,319
	Fox	69,507	99,296
Maximum Sustainable Yield	Schaefer	72,889	100,453
	Fox	98,334	104,783

In recent years price of fish and fuel has been fluctuating a lot. These fluctuations are causing the cost and venue changes to the fishery. Figures 10 and 11 shows how the open access equilibrium points might change with the changes in revenue and cost.

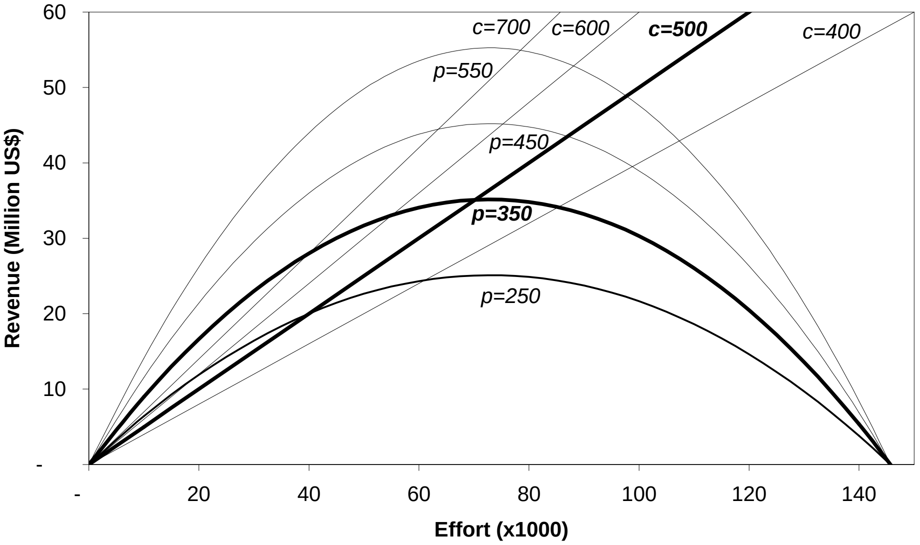

Figure 10: Open Access Equilibrium situation in Maldivian Skipjack tuna fishery based on the Schaefer model. Bold lines show the current situation.

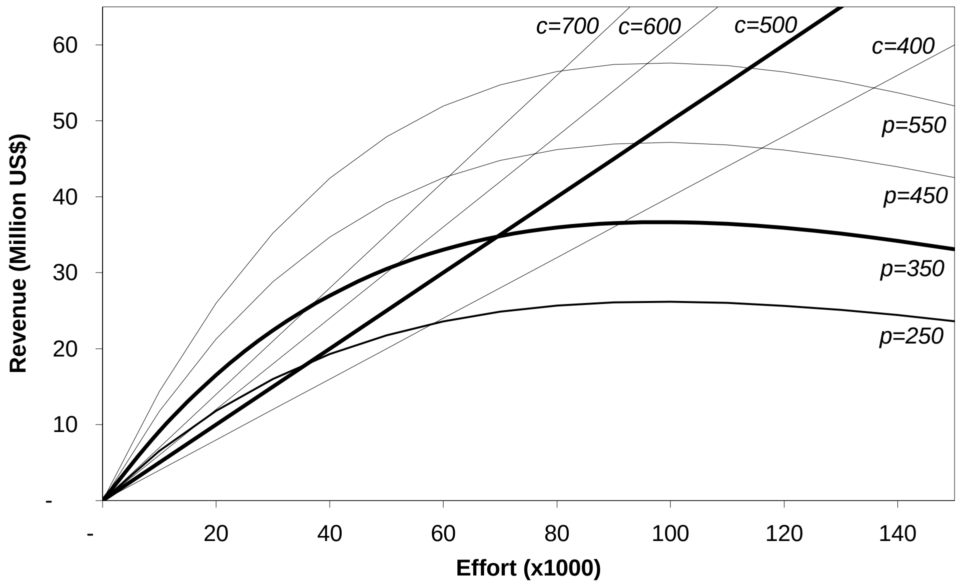

Figure 11: Open Access Equilibrium situation in Maldivian Skipjack tuna fishery based on the Fox model. Bold lines show the current situation.

Since the price of fish and cost of fuel are the major components of the revenue and cost, table 10 is constructed aiming to show how the profitability of the fishery might be changing with the changes in the fish price and cost of fuel. Calculations are based on a standard vessel of 2005; that is a vessel with 192 horsepower engine catching 1.5 tonnes per trip. The table is showing how the net revenue per trip would change with the change in fuel and fish price.

Table 10: Table shows how net profit per fishing trip might change with the changes in cost and revenue. Calculations are based on 2005 values. Values are in US$.

		%Change in Fish Price										
		-100%	-80%	-60%	-40%	-20%	0%	20%	40%	60%	80%	100%
%Change in cost of Fuel	100%	-671	-601	-531	-461	-391	-321	-251	-181	-111	-41	29
	80%	-603	-533	-463	-393	-323	-253	-183	-113	-43	27	97
	60%	-534	-464	-394	-324	-254	-184	-114	-44	26	96	166
	40%	-466	-396	-326	-256	-186	-116	-46	24	94	164	234
	20%	-397	-327	-257	-187	-117	-47	23	93	163	233	303
	0%	-329	-259	-189	-119	-49	**21**	91	161	231	301	371
	-20%	-261	-191	-121	-51	19	89	159	229	299	369	439
	-40%	-192	-122	-52	18	88	158	228	298	368	438	508
	-60%	-124	-54	16	86	156	226	296	366	436	506	576
	-80%	-55	15	85	155	225	295	365	435	505	575	645
	-100%	13	83	153	223	293	363	433	503	573	643	713

6. DISCUSSION AND CONCLUSION

The regression results show that the both Schaefer and Gompertz/Fox models aim to explain most of the variation found in the empirical data. The Fox model seems to give a slightly better fit than what is found in the Schafer model, indicated by the higher adjusted R square of the Fox model (0.77 versus 0.71 for Schafer model). Plot of CPUE towards effort (Figure 7) indicates that the linear model (CPUE vs. Effort) possibly introduces a systematic error, as a curved, non-linear CPUE-effort relationship is indicated by the empirical data. The Fox model offers a log-linear relationship which gives a better fit, but a certain systematic error seems to maintain. A Richard's type of model (also referred to as the Pella-Tomlinson model) introduce a parameter allowing both convex and concave the CPUE-effort relationship (e.g. squeezing the MSY-level to the left or right of the two models applied in this study). Introducing yet another parameter on the other hand also increases estimation error in the model. Given the limited data available, the alternative of introducing the Richard model was rejected.

Based on the analysis catch and effort level of the last few years are out of the sustainable harvest curve and catch level should be coming down. Open access equilibrium effort level (E_{OA}) is situated in the same area in both models, around 70,000 standard effort units. This level of effort was passed already in 2002 and the effort still increases. Both models also show E_{OA} to be below the E_{MSY} level, though not too far from E_{MSY}. Revenue and cost being the factor that moves E_{OA} along the equilibrium harvest curve, future changes in fuel and fish price would determine if this fishery will be stabilising at MSY or below it.

The actual E_{AO} might however be higher than the estimated because Maldivian fishers do not have a fixed salary; they share the profit and also the risk. In islands where opportunities for alternative employments are low, fishers would produce a higher effort in open access because of the lower opportunity cost of labour.

The current effort level is beyond the maximum sustainable yield effort level (E_{MSY}) as estimated by the Schaefer model. The Fox model indicates that this fishery is yet to reach its E_{MSY}.

New generation of vessels coming into this fishery are larger and more fuel consuming. These vessels are also designed for multi-day fisheries and have better bait holding capacities. Increased efficiency of these vessels may in fact increase the revenue and may move the position of E_{OA} to a higher effort level, in spite of the increased fuel cost. For the last few years catch has continued to be above the equilibrium levels estimated by the models of this study (Figure 9). This may indicate improved fishing efficiency or simply reflecting the fact that an equilibrium level is not obtained.

In the calculations the skipjack tuna purchasing price by the government company is assumed to represent the average price per unit of harvest, being the only documented price available over time. As mentioned earlier the GG category of yellowfin tuna reaches much higher prices, almost three times higher than for skipjack. Most of the local consumers and cottage industry for Maldive Fish also often pay a higher price than the companies.

Export of GG yellowfin tuna to Japanese and European market started in the late 90s. Some of the mechanised vessels in skipjack tuna fishery moved over to the yellowfin fishery and many new vessels joined this fishery; the fishery is still developing rapidly. Increased export of Maldive Fish starting from the year 2000 led to an expansion in the cottage industry for the Maldives fish. This expansion increased the demand for skipjack tuna consequently increasing the average price of skipjack tuna in the local market. These observations suggest that most likely revenue from the fishery may be underestimated.

OSY of this fishery at the interest rate of 3% was estimated to be around 74,000 tonnes per year, which is not too far from the MEY. An increase in interest rate would move OSY towards OA equilibrium. As for now this fishery is an open access fishery, each individual fishers' aim is to maximise his immediate gain. Moreover, most of the fishers are poor and their income from fishery hardly meets their daily needs. For this reasons for Maldivian fishers there is little incentive to try to achieve OSY or even MEY.

In the last report of the Scientific Committee of IOTC they stated that "*No quantitative stock assessment is currently available for skipjack tuna in the Indian Ocean. The range of stock indicators available to the Scientific Committee do not signal that there are any problems in the fishery currently*", and their management advice is "*there is no need for immediate concern about the status of skipjack tuna*" (IOTC, 2006b). Their advice is mainly based on the trend that is observed in many fisheries, declining catch with the increasing effort, has not been seen in the Indian Ocean skipjack tuna fishery.

This analysis indicates that with the current prices and costs Maldivian skipjack tuna fishery may not be biologically overfished. High cost of effort is preventing the fishery from moving beyond the effort of MSY. At the moment, increasing cost of effort seems to be the main concern in this fishery. If the current trend of increasing fishing cost continues, and if not balanced by an increase in revenue by increasing the price of catch efficiency, very soon the whole skipjack tuna fishing industry may face an economic collapse and consequently a reduced effort. Increased efficiency of vessels and price increase may radically alter this conclusion.

A critical assumption in the models presented here is that subjected Skipjack tuna stock is exploited solely by Maldivian fishers. This assumption is based on the growing evidence that skipjack tuna is less migratory than most of the other tuna species. Tagging experiments carried out in Maldives during the 90s' show that Maldivian species to a very low degree migrate to other areas (Shiham Adam & Sibert, 2002). Large scale tagging experiment covering the whole Indian Ocean and Maldives are however needed to indicate the level of migration from other areas to Maldives. Such study is now being conducted by Indian Ocean Tuna Commission (IOTC), but it may still be a few years until the result of this study is available (IOTC, 2006b).

Determining the boundaries of this skipjack tuna stock is going to be the key to the management and stock assessment. If this stock turned out to be a shared stock, use of FAD by purse seines in the West Indian Ocean could be having a potential effect on the Maldivian bait boat fishery. Even though there is little emigration from Maldivian waters to the rest of the Indian Ocean, recruitment for Maldivian skipjack tuna may take elsewhere in the West Indian Ocean.

By each technological improvement, from the traditional sailing vessels to mechanised vessels in 70s, introduction of global positioning devices in 90s and then to new generation of bigger vessels capable of multi-day fisheries, Maldivian fishers have been increasing their range of searching for fish. By doing so they are exposed to larger biomasses, which may be regarded as an increased fish stock. At this point the boundaries of the stock are not known, question remains to be answered. However if an increased stock size (if there is any increase) is found to be due to an increase in search area, being due to technological advances, the conclusions presented here may have to be dramatically altered.

In Maldivian tuna fishery it may not be entirely correct to define short term harvest as just a function of effort and stock size. Availability of bait is another extra component that largely determines the harvest in bait boat fishery. No matter what the stock size or effort level is, there won't be any harvest without bait in this fishery. As the abundance of bait shows seasonal fluctuations, during the seasons when bait abundance is low fishermen spends longer time searching and harvesting bait, effectively increasing their fishing effort.

Major finding from this analysis is that the fishery may not be biologically over exploited due to the high cost of effort. The study also indicates that effort level could be coming down in future. It is good news that fishery may not be over exploited easily. However, reduction of effort level could means loosing the only option of livelihood for many fishermen in the islands. Given that a high employment is the main objective, the immediate problem to address in this fishery seems to be reduction of cost of effort. The same goes to maximising sustainable yield, while resource rent could not be maximising could not be obtained without significant effort reduction.

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APPENDIX 1

Table A: Catch Composition by mechanised vessels 1985 – 2005

	Skipjack	Yellowfin	Other tuna related species	Other Marine fish	Total
1985	42,005	5,715	2,914	3,020	53,654
1986	45,099	5,178	1,810	2,377	54,464
1987	41,676	6,522	2,145	2,339	52,682
1988	57,966	6,366	2,119	2,167	68,618
1989	57,671	5,972	2,842	2,310	68,794
1990	59,724	5,225	4,258	5,068	74,275
1991	58,715	7,649	3,879	8,450	78,694
1992	58,269	8,628	5,545	7,343	79,785
1993	58,452	10,006	8,878	9,936	87,273
1994	68,453	12,859	6,348	13,198	100,858
1995	69,406	12,319	6,416	13,844	101,985
1996	65,794	12,276	10,173	14,779	103,021
1997	68,066	12,838	4,748	13,092	98,743
1998	77,489	13,822	7,446	13,072	111,829
1999	91,721	14,155	5,179	9,853	120,908
2000	79,455	12,139	5,990	16,184	113,768
2001	87,847	14,540	6,485	14,570	123,442
2002	113,652	21,502	6,793	15,010	156,957
2003	103,864	19,546	7,135	15,352	145,897
2004	109,438	22,441	6,356	16,325	154,560
2005	131,121	21,461	8,094	19,353	180,029

Table B: Fish purchasing price by companies, fuel price and Average exchange rate 1985 – 2005.

Year	Fish Price (Mrf/kg)	Fuel Price (Mrf/L)	Average Exchange Rate (Mrf/US$)
1985	1.50	2.70	7.10
1986	1.80	2.70	7.15
1987	1.80	2.60	9.22
1988	2.00	2.60	8.78
1989	2.00	2.60	9.04
1990	2.00	3.10	9.51
1991	2.15	3.60	10.25
1992	2.40	3.25	10.57
1993	2.50	3.25	10.96
1994	2.80	3.25	11.59
1995	3.00	2.90	11.77
1996	4.00	3.00	11.77
1997	3.00	3.30	11.77
1998	3.50	3.20	11.77
1999	3.50	3.20	11.77
2000	3.50	4.06	11.77
2001	3.00	4.20	12.24
2002	3.50	5.00	12.80
2003	3.50	4.65	12.80
2004	2.90	5.50	12.80
2005	4.35	6.70	12.80

APPENDIX 2

Open Access Equilibrium:

Schaefer: $E_{OA} = \left(\frac{c}{p} - qK\right) \times \frac{r}{q^2 K} \quad \Leftrightarrow \quad E_{OA} = \frac{c}{p\alpha_2} - \frac{\alpha_1}{\alpha_2}$

Fox: $E_{OA} = \left(\ln qK - \ln\left(\frac{c}{p}\right)\right) \times \frac{\mu}{q} \quad \Leftrightarrow \quad E_{OA} = \left(\beta_1 - \ln\left(\frac{c}{p}\right)\right) \times \frac{1}{\beta_2}$

Maximum Sustainable Yield:

Schaefer: $E_{MSY} = \frac{r}{2q} \quad \Leftrightarrow \quad E_{MSY} = \frac{\alpha_1}{2\alpha_2}$

Fox: $E_{MSY} = \frac{\mu}{q} \quad \Leftrightarrow \quad E_{MSY} = \frac{1}{-\beta_2}$

Maximum Economic Yield:

Schaefer: $E_{MEY=} \frac{r(pqK - c)}{2pq^2 K} \quad \Leftrightarrow \quad E_{MEY} = \frac{c - \alpha_1 p}{2p\alpha_2}$

Fox: $E_{MEY} = \frac{\mu}{q}\left(1 - \omega\left(\frac{ce}{pqK}\right)\right) \quad \Leftrightarrow \quad E_{MEY} = \frac{1-\omega}{\beta_2}$

ω = Lamberts function: $\omega.e^{\omega} = \frac{c \times e}{pqK} \Rightarrow \omega.e^{\omega} = \frac{ce^{1-\beta_1}}{p}$

Optimum Economic Yield:

Schaefer: $E^* = \frac{(1+\delta)\cdot(-c + pqK)}{(2+\delta)\cdot p \cdot \left(\frac{q^2 K}{r}\right)} \quad \Leftrightarrow \quad E^* = \frac{(1+\delta)\cdot(-c + p\alpha_1)}{(2+\delta)\cdot p\alpha_2}$

Fox: $E^* = \frac{\mu}{q}\left(1 + \delta - \omega\left(\frac{ce^{1+\delta}(1+\delta)}{pqK}\right)\right) \Leftrightarrow E^* = \frac{-1 - \delta + \omega\left(\frac{c}{p}(1+\delta)\cdot e^{1+\delta-\beta_1}\right)}{\beta_2}$