Essays on Natural Resource Management: Managing Industrial Marine Fisheries of Bangladesh

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Declaration

I declare that this thesis is my own original research work done at the Australian National University. It contains no material which has been accepted for any other degree or diploma, or any copy or any paraphrase of another person's material except where the due acknowledgement is given.

Nazneen Kawshar Chowdhury

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Abstract

This thesis is a combination of five essays: one introductory essay (Chapter 1), three core essays (Chapter 2, 3 and 4) and one concluding essay (Chapter 5). The first essay (Chapter 1) gives an overview of management on marine capture fisheries. The second essay (Chapter 2) investigates the effect of input control on vessels' performance of the industrial marine fisheries of Bangladesh and the vessels' performance in this study is measured in term of technical efficiency and productivity. The third essay (Chapter 3) estimates biological reference points of industrial marine fisheries of Bangladesh in order to find out the current status of the industrial marine fisheries. The fourth essay (Chapter 4) measures the economic performance of the industrial marine fisheries of Bangladesh. The fifth essay discusses the impact of traditional command and control approaches to marine fisheries management in light of evidence from industrial marine fisheries of Bangladesh.

Chapter 1 gives an overview of management of marine capture fisheries. Challenges in marine fisheries management; and policy evolution of marine fisheries management from biological, economic and eco-system perspectives are covered in this Chapter. The Chapter finally focuses on the importance of economic perspectives and analyses in fisheries management that allow managers to generate performance criteria to quantify management goals; to employ models to compare management strategies and policies; and to use methods to calculate performance criteria and adjust policies and regulations to better achieve targets.

Chapter 2 is a first kind of study to measure performance of vessels of industrial marine fisheries of Bangladesh. A panel data set for the period 2001-2007 for Translog production function and technical efficiency effect model is used to measure efficiency; and Total Factor Productivity (TFP) is used to measure productivity. Theoretical consistencies of Translog production function for vessel, output elasticity associated with all inputs, elasticity of scale and marginal productivity of all inputs are examined in this study. Technical efficiency, technical progress and scale change are also estimated to find out the sources of productivity. The study shows that vessels are producing below the maximum level of output and are too small in their scale of operation. It also shows input control

induces vessels' operators to use unregulated inputs. The study shows that the input control that is employed in industrial marine fisheries of Bangladesh fails to increase vessels efficiency and productivity. Hence, an alternative management strategy is needed to increase technical efficiency and productivity of the industrial marine shrimp and fish fisheries of Bangladesh.

Chapter 3 measures the biological reference points of the industrial marine fisheries of Bangladesh. Biomass dynamic models: a dynamic version of surplus production models, are used to estimate biological reference points and a time series data for the period 1992-2007 is used. This study is a first of its kind in terms of study area and use of models to calculate the biological parameters. This study covers the area that is beyond 40 metres depth within the Exclusive Economic Zone (EEZ) of Bangladesh and uses Clarke, Yoshimoto & Pooley (CY&P) models to calculate the biological parameters. Ordinary Least Square (OLS) technique is applied to calculate the biological parameters. Using these biological parameters- the current abundance of biomass, biomass at Maximum Sustainable Yield (MSY) and the biomass at the steady-state are measured. The study shows that the shrimp stock of the industrial marine fisheries is over-exploited and the fall in catch per unit effort (CPUE) over time of the industrial marine shrimp fishery is due to the fall in stock size. On the other hand, the fish stock of the industrial marine fisheries is under-exploited and the fall in CPUE over time of the industrial marine fish fishery is due to inadequate knowledge and information on the availability of the sizes of different fish stocks and lack of technological developments for harvesting the new resources. The study also shows that to maintain steady-state equilibrium and an adequate growth rate of both shrimp and fish, fishing patterns need to be modified. The study also indicates that the current management strategy fails to increase the level of high-valued shrimp stocks and to increase the catch level of the low-valued stocks. Hence, an alternative management strategy is needed for industrial marine shrimp and fish fisheries of Bangladesh.

Chapter 4 is also a first study of its kind that covers shrimp and fish of the industrial marine fisheries of Bangladesh. This study develops two single-species and single-fleet models separately for both shrimp and fish fisheries. Current and potential economic performance of both shrimp and fish fisheries in this study are measured using three different bio-economic models, including a bio-economic model for open access fishery, a static profit maximization problem and a dynamic present value-maximization problem in continuous time. For both shrimp and fish fisheries of industrial marine fisheries of Bangladesh, this is the first kind of study that uses the Gompertz curve in the biological growth models; biological parameters are derived following CY&P models; price of harvest and cost per unit effort are estimated separately. The equilibrium biomass, effort and profit at bio-economic equilibrium of open access fishery, at static Maximum Economic Yield (MEY) and dynamic MEY are compared with the MSY. Sensitivity to changes in the price of harvest; changes in cost per unit effort and changes in social discount rate on biomass are also examined. The study shows that excessive use of efforts makes both shrimp and fish fisheries economically inefficient in the form of low stock biomass and profit. The study suggests that both economically viable (with high profit) and ecologically sustainable (with high stock biomass) shrimp and fish fisheries in industrial marine fisheries of Bangladesh could be achieved by setting management target at the MEY level and hence excessive use of efforts in both shrimp and fish fisheries needs to be reduced.

Chapter 5 discusses the impact of traditional 'command and control' approach to reduce overcapacity and overexploitation in marine fisheries management with an evidence of industrial marine fishery of Bangladesh. The causes of overfishing and overcapacity in fisheries management; and traditional 'command and control' approaches to fisheries management also cover to analyze the impact. The evidences conclude that command and control approaches to the industrial marine fisheries management of Bangladesh fail to increase efficiency and to control overcapitalization. Evidence shows that fisheries suffer overcapacity and fisheries are economically unprofitable. As marine fisheries legislation in Bangladesh is too old and fisheries policies are more focused on increased production with little emphasis on conservation or sustainable fisheries management, a reform in legislation and management systems of the industrial marine fisheries of Bangladesh is needed. To protect economic and biological overfishing, a correct management target and right-based approach that is, an incentive adjusting approach is needed so that the fisheries can be both economically profitable and biologically sustainable.

Key words: technical efficiency, productivity, biological reference point, biomass dynamic models, economic performance, single-species and single-fleet model, bio-economic models, profit maximization, fisheries management and policy

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Chapter 1

Natural resource management: an overview of marine capture fisheries

1.1 Introduction

Since the early 1980s concerns about unsustainability of marine fisheries have grown, as stocks continued to decline despite the adoption of the United Nations Convention on the Law of the Sea (UNCLOS) in 1982 (Garcia 2010). Overcapacity, overharvesting, poor economic returns and habitat damage are considered the main reasons for the depletion of world fish stocks (Hilborn et al 2003). Over the last 30 years global fisheries fleet has increased over 75 percent and Asia accounts for highest number of vessels (Food and Agricultural Organization (FAO) 2007). An increase both in vessel numbers and in vessel technology has enhanced the capacity of the global fleet and facilitated access to an expanding range of marine fisheries resources. Despite the expansion of fishing efforts, the global marine catch has been stagnant for more than a decade and the difference between the global cost of harvest and value of harvest has narrowed. Hence, the world fisheries are underperforming or subject to economic overfishing and global marine catch has stagnated at a level of 80-85 million tonnes since 1990 (Willmann & Kelleher 2010). According to the Food and Agricultural Organization (FAO) report (2011), 57.4 percent of the world's marine fisheries are fully exploited in 2009, producing at, or close to, their Maximum Sustainable Yield (MSY) and there is no room for further expansion in catch and some stocks are at risk of decline if not properly managed. The report also shows that among the remaining stocks 29.9 percent are over-exploited, depleted or recovering from depletion and yielding less than MSY and 12.7 percent are under-exploited or moderately exploited, where under-exploited stocks are low-valued stocks/species.

It is widely recognized that overfishing is increasingly threatening the world's marine capture fisheries (Jackson et al 2001; Myers & Worm 2003). On the other hand, Sunken Billions Study shows a significant loss of potential economic rent in the global fishery due to massive overcapacity in the global fleet (Arnason et al 2009). As a result, marine fisheries have become a main focus of societal attention (Garcia 2010).

Between 1990 and 2030 the world's population is likely to increase by 3.7 billion, where ninety percent of this increase will be in developing countries (Bojo 2000). Increasing trends of population increases the demand for consumption in developing countries. The FAO report (2009) shows that, in the past four decades, the per capita fish consumption has increased from an average 9.9 kg in the 1960s to 16.4 kg in 2005 and the human consumption of fish in 2005 is 107 million tonnes, where Asia accounted for two-thirds of total consumption. FAO (2009) estimated that at least 50 percent of total animal protein intake in developing countries (such as Bangladesh, Cambodia, Ghana, Indonesia, etc.) comes from fish. During the past three decades the number of fishers and fish farmers has also grown at a higher rate than the world's population growth rate and Asia has by far the highest share and growth rate in the number of fishers and fish farmers (FAO 2007). Increases in the number of fishery workers in many developing countries are due to the growing poverty trap, and in the absence of an alternative, is considered a livelihood of last resort.

In addition, globalization increases the trade and increases the competition in exploiting fish resources. Fish and fishery products export reached US $85.9 billion in 2006 in the world and total production increased more than 37 percent, in circumstances where 79 percent fishery production of the world comes from developing countries (FAO 2009). In many fish exporting developing countries, the fisheries play an important role to the economy. Fish exports in developing countries grew from US $1.8 billion in 1976 to US $24.6 billion in 2006 and developing countries contributed 59 percent (31.6 million tonnes) of world exports of fish and fishery products; 35 percent (by quantity) of world exports of fish meal; and 70 percent (in terms of quantity) of world non-food fishery exports (FAO 2009). In a globalizing fisheries world, the interdependence between developing and developed countries is also increasing. The fishery industry of developing countries relies on developed countries' markets. In recent decades, the flexibility of custom duties increased the access of fishery products in the developed countries' markets from developing countries. FAO report (2009) shows that in 2006, 40 percent of the value of fish and fishery products imported by developing countries originated from developed countries, and 25 percent of the value of fisheries exports was traded between developing countries.

Economically healthy fisheries are fundamental to achieving goals for the fisheries sectors such as improved livelihoods, food security, increased exports and the restoration of fish stocks (World Summit on the Sustainable Development (WSSD), 2002). But, most of the world's fisheries including industrial marine fisheries of Bangladesh suffer overfishing and overcapacity; and the management of fisheries faces many challenges in the conservation and management of marine fisheries (Clark 2010). Many differences exist across fisheries, but, almost all fisheries consist of some common characteristics[1]. Some of these problems, such as tragedy of the commons[2], are widely recognized, but others have been somewhat ignored. This thesis examines the management of industrial marine fisheries of Bangladesh. Industrial marine fisheries of Bangladesh are a common property resource, which are subject to possible overexploitation in the absence of efficient and effective management.

The Bangladesh coastline extends for 714 km with an Exclusive Economic Zone (EEZ) of 166,000 square km of which 44 percent is continental shelf. The marine water extends beyond the continental shelf, measuring 200 nautical miles from the base line (10 fathoms) including rivers and estuaries. Marine fisheries of Bangladesh consist of two fisheries: artisanal[3] fisheries and industrial[4] fisheries. The industrial fishing vessels are divided into two broad categories: shrimp[5] fleet and fish[6] fleet. The management of the industrial marine fisheries is mainly governed by the Marine Fisheries Ordinance 1983 and the Marine Fisheries Rules 1983. The management system for shrimp vessels is closed season, licensing and input control. On the other hand, the management system for fish vessels is licensing and input control. Industrial fleets of the open access industrial marine fisheries have been expanding over time (Marine Fisheries Department (MFD) 2009).

[1] Such as fisheries are common pool resources, uncertainty in fisheries, fishers before fish and ecosystem (Grafton et al 2010a).

[2] In an open access resource few issues, such as lack of property rights over the fish, effective management of the resource, cooperation among harvesters and free entry into a fishery by outsiders increase negative externalities in fisheries, known as tragedy of the commons (Grafton et al 2006b; Hardin 1968).

[3] The *artisanal fisheries* are small-scale onshore fisheries and fishing occurs up to 40 metres depth with mechanized and non-mechanized boats.

[4] The *industrial fisheries* are large-scale offshore fisheries and fishing occurs beyond 40 metres depth within the EEZ of Bangladesh with industrial vessels.

[5] Vessels in the shrimp fleet are double-rigged vessels, fitted with two side beams from which two shrimp-trawl nets are simultaneously operated. A standard shrimp vessel is made of steel hull and mesh size of the net at the cod-end is 45mm.

[6] Vessels in fish fleet are stern vessels with a single-rigged trawl-net operated behind the vessels. These vessels generally have both wooden and steel hulls and the mesh size of the net at the cod-end is 60mm.

Marine shrimp species[7] and fin fish species[8] are commercially important and are normally harvested by the industrial fishing vessels. These vessels were officially introduced in 1984 with a large number of imported second hand trawlers/vessels. According to the data of the MFD (2009), between 2001 and 2007, the major amount of total targeted catches of shrimp comes from shrimp fleet (99.09 percent) and the amount of total targeted catches of fish comes from fish fleet (71.93 percent). Both shrimp and fish are demersal[9] resources of the industrial marine fisheries. The management conditions allow both shrimp and fish fleets to catch 30 percent of bycatch, but due to the use of different gear and mesh sizes, the average bycatch of both fleets, in fact, are very low. So, the bycatch of both shrimp fleet (28.73 percent fish) and fish fleet (0.91 percent shrimp) are ignored in this research and the targeted resources (shrimp and fish) are considered as homogeneous biomasses. On the other hand, both shrimp and fish fleets are operated with two different sets of gear: double rigger (for shrimp) and stern trawl (for fish) with 45mm and 60mm mesh sizes of the net at the cod-end, respectively. All vessels within the fleets are considered as homogeneous vessels in terms of gear. Both fleets are independent in their targeted catch. Hence, the industrial marine fisheries of Bangladesh in this research are considered as single-species and single-fleet for both the shrimp fishery and the fish fishery. This research has done three different studies on industrial vessels' performance, stock assessment and economic efficiency.

The objective of this Chapter is to give an overview of marine fisheries management. The remainder of this Chapter is divided into five sections. Section 1.2 describes challenges in marine fisheries management. Section 1.3 discusses the policy evolution of marine fisheries management from biological and economic perspectives followed by eco-system perspective in Section 1.4. Section 1.5 focuses on the importance of economic perspective in fisheries management. Section 1.6 presents the structure of the thesis.

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[7] The key commercial marine shrimp species those are harvested by the industrial vessels are tiger shrimp (*Penaeus monodon*) and brown shrimp (*Metapenaeus monodon*). *Penaeus monodon* (tiger shrimp) is the most valuable and hence the targeted species. But the highest (almost two thirds of the total) contribution to the total catch is from *Metapenaeus monodon* (brown shrimp).

[8] More than ninety fish species are commercially important. These fall under the common group. The major commercial fin fish species exploited by the industrial vessels are pomfret (*Pampus argenteus*), goatfish (*Upenuus sulphureus*), bream (*N. japonicas*), lizard fish (*Saurida tumbil*), grunter (*Popmadasys hasta*), red snapper (*Lutjanus johnii*) and carangid (*Arioma indica*) (MFD 2009).

[9] Demersal and ground fish are those that feed on ocean or lake bottoms and typically do not range over a wide area.

1.2 Challenges in marine fisheries management

The main challenge of marine fisheries is how to effectively achieve sustainable fishing and to stop overfishing (Metuzals et al 2010). In open access[10] fisheries resources use, the existence of market failure can lead to extinctions of fish stocks (Hartwick & Olewiler 1998). Lack of property rights to the fish can lead to overfishing, and even lead to the extinction of fish species because fish stocks are common pool resources (Hardin 1968) and have two distinct features (Grafton et al 2004). Firstly, the catches in common pool resources are rivalrous, where fishing by one person reduces the catch available to others and secondly, common pool resources are costly to effectively control the access and the harvest from them. In common pool resources, it is difficult to monitor the fishers and to enforce the regulation. In many fisheries, incentives for fishers do not exit and hence, fishers do not care about the sustainability of resource, rather care about their own interest. As a result, difficulties exist in implementing adequate monitoring, control and surveillance. Open access/common pool cannot achieve an efficient allocation of resources without some form of government intervention, the creation of private property rights or both (Hartwick & Olewiler 1998). For example, the common property problem in many fisheries requires controls of some sort on fishing effort and/or harvests. However, many open accesses are in danger of being exhausted even with various types of government regulation. Many regulations have not been successful due to putting fishers before fish, which has contributed to the problems of overfishing (Larkin 1978). Munro & Scott (1985) argue that unlike other renewable resources, the common property fishery resources are difficult to manage effectively.

In many fisheries, regulations and management are mainly designed to achieve the sustainable level of fishing mortality by restricting the number of vessels into a fishery or by limiting the length of vessels permitted to fish. That said that fishers often substitute their inputs (Kompas et al 2004; Squires 1987; Wilen 1979). Failure to understand the incentives of fishers and respond to regulations leads to poor outcomes in fisheries management (Hilborn et al 2005). An incentive-based approach helps to ensure the individual incentives of fishers coincide with the overall interests of the

[10] Open access natural resources include many fisheries and environmental resources, such as air and water. Fisheries and environmental resources have remained as open-access for long period of times (Hartwick & Olewiler 1998).

fishery (Grafton et al 2006a, 2010a; Hilborn 2007b) and allows fishers either individually or collectively, to have catch shares or rights over particular fishing locations. To conserve fish stocks managers can change the dynamics of fishing behavior from racing to catch the fish before someone else, and hence minimize harvesting costs and protect the future returns from fishing.

Another important challenge of managing marine fisheries is unforeseen fluctuations. There exists an inherent uncertainty in marine capture fisheries that will never be overcome (Ludwig et al 1993). Much of the fluctuations in fish stocks are results of environmental changes, such as increases in surface ocean temperatures, ocean acidification resulting from increased atmospheric carbon dioxide, which is beyond control. Effective management of fisheries requires explicit recognition of these uncertainties, however what method should be used to deal with uncertainty is not yet widely agreed upon (Clark 2010). The challenges of overfishing and conservation are also magnified by climate change (Beddington et al 2007; Grafton et al 2010a). Externally generated changes to the marine environment such as oceanic pollution from terrestrial runoff and from ocean dumping; increased variability of ocean current, rising sea levels, and changes in salinity are important challenges to effective fisheries management (Beddington et al 2007; Clark 2010). Fisheries productivity on local and global scales can be reduced due to these externally generated changes and these need to be effectively managed to ensure the sustainability of the world's fisheries. Climate change adversely affects fish stocks by altering physiology, behavior and growth, development, reproductive capacity, mortality and distribution (Perry et al 2009). Climate change also alters the productivity structure, and composition of the eco-systems on which fish depends for food and shelter (Brander 2010).

Management of fisheries and of marine eco-systems has not yet succeeded in dealing adequately with overfishing, which is of greater immediate concern than the effects of climate change (Beddington et al 2007). Overfishing affects biodiversity in a variety of ways, such as through directed catches (direct mortality on target and overfishing), impact on non-target species (catchability of the bycatch, productivity and sustainable mortality rate), and impact on fish habitats (fishing gear, such as drift nets, long-lines, set nets, pound nets, and trawl gear/bottom trawling affect)[11]; illegal fishing (such as sea turtles and shark) (Agnew et al 2008; Berkes et al 2006; FAO 2002a); widespread piracy (Berkes et al 2006; Heithaus et al 2008) as well as unreported and unregulated catch (FAO 2001, 2002b; Metuzals et al 2010). The key factors encouraging overfishing are rising demand for seafood; serious overcapacity of fishing fleets; high profitability, a pernicious combination of poorly crafted regulations and weak enforcement in developed countries; corruption and concealment and the ease of obtaining false documentation in developing countries; and failure to regulate high seas fishing (Metuzals et al 2010). As a result, most fish stocks are in decline (Myers & Worm 2003; Worm et al 2005). There is, for example, a decrease in the average size of tuna (Golet et al 2007), and reduction in the marine food chain (Pauley et al 1998; Myers et al 2007). Recognition of these impacts of fishing on marine eco-systems has led to the development of eco-system approaches to fisheries management (Garcia et al 2003; Pikitch et al 2004).

An effective management system can protect fish stocks and effective management depends on efficiency, optimality and sustainability (Perman et al 2011). Feasibility of sustainable policies depends on a variety of factors, including the degree of substitutability between fish stocks and produced capital, technology/technical change, secure property rights and efficient pricing. A principle of sustainability is not to allow the stocks to decline, which means that there must be a sufficiently large stock of the marine resources to generate a flow that can be sustained over time (Hartwick & Olewiler 1998). But, fisheries management faces severe problems of implementing controls such as the monitoring and enforcement of catch quotas; prevention of illegal fishing; monitoring and control of bycatch and discards; and control of habitat degradation (Clark 2010) and hence marine fisheries experience overcapacity, overharvesting, habitat damage and poor economic returns (Hilborn et al 2003). Strong management can ensure that biological targets are met, but it is essential that regulations are enforceable, and this has often proved to be difficult. Less-than-perfect enforcement can lead to illegal fishing, poor scientific data, and a failure to meet biological targets (Beddington et al 2007). Every method of fisheries management requires enforcement of the regulations (Clark 2010), but it is recognized that existing governance systems for

[11] For example: Auster & Langton 1998; Barbier 2000; Barbier & Cox 2004; Collie et al 2000; Crouse 2000; Harrington et al 2005; Hughes 1994; Mc Manus & Polsenberg 2004; Nichols et al 2010; Pauly 2007; Peckham et al 2007; Rice & Ridgeway 2010; Roberts 2002; Schwinghamer et al 1996; Thrush et al 1998; Watling & Norse 1998.

high sea fisheries failed totally (Hilborn 2007a). Current management techniques and strategies that are widely used in the common pool marine fisheries are: a complete lack of management or pure open access; limited entry such as license restriction; closed seasons and area closures; input control such as vessel tonnage, mesh size, gear restrictions; harvest control such as Total Annual Catch (TAC); and right-based fishing such as Individual Transferrable Quotas (ITQ) (Clark 2010). The next section gives an overview how these management techniques comes into effect over the year since 1950.

1.3 Policy evolution: biological and economic perspectives

Prior to World War II, there was no real consensus that renewable resources, such as fisheries, needed active management as very few of the world's fisheries were subject to any control at that time. The post-war boom in ship building in a few nations such as Soviet Union, Japan, China, South Korea and Poland introduced large trawl fleets to fish the world's fish stocks (Wilen 1999). As a result, exploitation rates rose exponentially, evidence of biomass declines began to accumulate and conflicts began to emerge between domestic and foreign fleets. Hence, the rational of renewable resources management emerged in the 1950s from two perspectives: biological and economical. On the other hand, mathematical modeling started in the early years of the 20th century (Baranav 1918) and extended during the first half of that century (Graham 1935) and mid-century (Beverton & Holt 1957; Ricker 1954; Schaefer 1954).

The conceptual foundations for a biological rationale for management are established by the studies done by Beverton & Holt (1957) and Schaefer (1957); and economical rationales for management are established by Gordon (1954) and Scott (1955). The studies based on economical rationale for management revealed the implication of open access resource use (Gordon 1954) and the concept of resource conservation (Scott 1955). On the other hand, the studies based on biological rationale for management revealed the concept of Maximum Sustainable Yield (MSY) by linking fishing effort, fishing mortality and stocks dynamics. MSY is used as a benchmark management policy as well as to identify conditions and symptoms of overfishing and the stock status.

In the 1960s, regulatory programs introduced worldwide originated with new paradigms based on biological rationale for management; however, none of these programs were established to address economic rationale for management. Restriction on fishing technologies, such as minimum mesh size or complete prohibition of certain gear types, were the most commonly used regulations (Wilen 1999). To conserve fish stocks, many voluntary regulatory bodies were formed and developed a number of multilateral agreements during the 1960s and early 1970s. But, lack of agreement over regulations and over enforcement meant that most of these tilted towards failure. During the same time, fisheries policy economists focused on normative issues to guide policy, other than MSY. Economists argued that society should be trying to maximize sustainable rent or economic yield and that restricting technology and prohibiting efficient gear types are ultimately folly if society is interested in economic returns from resource. Economists also defined the policy problems such as lack of property rights and open access incentive.

To manage resources over time, the dynamic theory of the sole owned fishery was introduced and the optimal steady-state was defined. Throughout the 1960s, resource economists continued to place great effort on understanding and clarifying the nature of dynamic formulations of the renewable resources problem. At the end of the 1960s, a methodological revolution of considerable consequence was introduced in the environmental and resource economics. The conceptual cores of ideas of static framework of welfare economics, externalities and public goods were introduced in environmental economics; and dynamic analysis in natural resource economics. In resource economics, optimal control theory (Pontryagin et al 1962) and calculus of variation (Crutchfield & Zellner 1962) were introduced to solve the optimal steady-state of the resources. As the natural resource use often involves the time paths of outputs and inputs in an essential way and involves decision-making over time (Hartwick & Olewiler 1998), later these conceptual ideas were introduced to describe the optimal use path for both renewable[12] and non-renewable[13] resources.

Given the property rights in most fisheries are incompletely defined, at the end of the 1960s new resource economists focused on the fundamental conservation of the

[12] A natural resource which supplies productive inputs to an economic system indefinitely is known as renewable resources, such as fish, forests, solar energy, water, atmosphere, etc. (Hartwick & Olewiler 1998). Renewable resources have the potential to regenerate new supplies to replace those used by the economic system, but, most renewable resources can be depleted or exhausted and can become non-renewable.

[13] Natural resource with finite stock/supply, once used up, is gone is known as non-renewable resource, such as, minerals, oil, gas, etc. (Hartwick & Olewiler 1998).

resource. They argued that resources can reach towards the economic optimum either fixing the property rights problem by creating property institutions or inducing efficient behavior by altering private incentives with prices or quantity mechanisms (Wilen 1999). In the early 1970s, property rights solutions were ignored and instead, Pigouvian solutions involving landings and vessel taxes were more focused to examine the pollution problem of fishing.

In 1975 Clark & Munro (1975) outlined the dynamic fisheries problem as a capital[14] theory problem and applied some of the new techniques emerging in the capital theory literature in economics. At nearly the same time in 1976, the United States and other coastal nations expanded their jurisdiction over territorial waters and fisheries up to 200 miles, from 3-12 miles. These actions opened up a new area of concern about transboundary stocks and stocks inhabiting areas, which do not fall into the territorial boundaries (Copeland 1990; Fisher & Mirman 1996; Munro 1990). With these changes in property rights, most of the world's fisheries came under a legal and administrative framework. In the same year, a new legislation[15] was created in the United States to regulate fisheries in the new Exclusive Economic Zones (EEZ), based on the argument promoting fisheries' economically efficient management rather than strictly biologically based management. Economists argued that these new institutional settings would improve economic efficiency in the use of renewable natural resources. But decision-makers in the Fisheries Management Council in the United States were more convinced about the biologically based management and accepted the recommendations of biologists about the level of Total Allowable Catch (TAC) to keep fisheries at the MSY level.

These management actions raised several questions (Wilen 1999) related to resource allocation, where the efficiency questions were totally ignored. Consequently several empirical and predictive analyses were done by the economists related to the problem of incomplete property rights that led to the overcapitalization and economic inefficiency of the fisheries. With the rapid changing status of the world's fisheries, in order to contain capital growth, economists argued (Anderson 1977) to prevent

[14] Most natural resources have some characteristics that make them very similar to capital, such as natural resources are used for consumption or in production process and hence, they are extracted or harvested; and yield productive service over time (Hartwick & Olewiler 1998).
[15] Fishery Conservation and Management Act (FCMA) 1976.

overcapitalization and suggested policy-makers consider the limited-entry[16] programs similar to the few fisheries[17] (Wilen 1999). But, the findings of the empirical analysis on limited entry program (such as the British Columbia salmon fishery) show that fishermen replaced older, smaller vessels with larger and high-powered vessels (Campbell 1991; Fraser 1979; Pearse & Wilen 1979). The policy-makers then introduced input-control (for example, in the British Columbia salmon fishery) by restricting vessel tonnage. As a result, fishers increased their vessel length and input control measure became unsuccessful as the changes in input restrictions induced fishers to substitute inputs with the unregulated inputs. Similar evidence of rent dissipation through substitution of regulated inputs with the unregulated inputs also showed in the Australian prawn and rock lobstar cases, British Columbia roe herring cases, and the Alaska salmon programs (Wilen 1999). Thus, input control failed to increase efficiency in many fisheries around the world, such as the mid-Atlantic sea scallop fishery (Kirkley et al 1995, 1998); longline fishery in Hawaii (Sharma & Leung 1999), Dutch beam trawler fishery (Pascoe et al 2001), English Channel fishery (Pascoe & Coglan 2002), British Columbia halibut fishery (Grafton et al 2000), Australia's banana prawn fishery (Kompas et al 2004), New South Wales, Australia ocean prawn trawl fishery (Greenville et al 2006) and in many other fisheries including the industrial marine fisheries of Bangladesh (see Chapter 2).

Following the failure of the fisheries management through input control, policy emerged in favor of using property rights, namely, Individual Transferable Quota (ITQ), that would establish the overall allocation in order to maintain stocks level at the MSY. In the early 1980s, both Iceland and New Zealand adopted ITQ programs followed by Canada, Australia and the Netherlands. The Organization for Economic Cooperation and Development (OECD) report (1997) shows that 55 fisheries around the world are managed using ITQs. Though, the United States has been slow to implement ITQ programs with four in place: mid-Atlantic surf clam and ocean quahog fishery, the South Atlantic wreckfish fishery, North Pacific halibut and sablefish fisheries (Hsu & Wilen 1997; Wilen 1999) ITQ programs worked well for decades in fisheries

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[16] In 1957, Scott proposed a limit on the number of fishermen to avoid wasteful expansion of the fleet and on the number of crew (Turvey & Wiseman 1957). The limited-entry programs control fishing mortality growth by a license limitation.

[17] South African pilchard and mackerel fishery (1953); Western Australia rock lobstar fishery (1963); Australian prawn fishery (1965); Canadian maritime lobstar program (1967); British Columbia salmon program (1968); several in Eastern Canada including herring (1970); the Bay of Fundy scallops, offshore scallops and lobster and ground fish fisheries (all in 1973); Alaska and Washington salmon fisheries (1974).

throughout the world (Kompas 2005) including Iceland, New Zealand, United States, Australia and Canada (Hannesson 2004). ITQ confers a number of benefits given that rights are transferable. Benefits include greater assurance of catch given harvesting rights and regulations can enable autonomous adjustment of fishing fleet (Kompas 2005; Grafton et al 2006b).

1.4 Policy evolution: single-species and eco-system (multi-species) perspective

Fisheries modeling determining sustainable yields are mainly focused on single-species fisheries (Funk et al 2000; Hilborn & Walters 1992; Motos & Wilson 2006) and mathematical modeling beyond a single-species approach to fisheries modeling did not arise until the 1970s and 1980s (Smith & Fulton 2010). Fisheries shifted gradually under a sustainable development paradigm, that is, in Ecosystem-Based Fisheries Management (EBFM) (Pikitch et al 2004) or Eco-system Approach for Fishery (EAF)[18] (Garcia et al 2003) following the United Nations Summit of Human Environment 1972 and World Conference on Environment and Development 1987. The sustainable development principles show the influence of large-scale development policies on fisheries and the fishery sector (Garcia 2010) and take account of externalities such as environmental influences on stock dynamics, species interactions, economic drivers, and performance.

Most recently, policies have taken account of management system itself and the way in which fishers interact with and respond to it. Fishers are also seen as part of a linked bio-physical, socio-economic and governance system (Smith & Fulton 2010) and adopt a precautionary approach to uncertainty (Pikitch et al 2004). These focuses arise from concerns about a number of wider impacts of fishing[19] such as discard of species other than target species or other commercially valuable species. Secondly, impact of fishing on threatened, endangered and protected species. Thirdly, impacts of certain gear types (mainly trawls and dredges) on habitats. Fourthly, impacts at the level of eco-system

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[18] The eco-system approach for fishery (EAF) was formalized in 2001 and the implication of EAF for governance stem for three sources of complexity related to the (i) fishery system; (ii) diversity and dynamics of the institution involved and (iii) strong influence of strong drivers (Garcia 2010).

[19] For example: Auster & Langton 1998; Collie et al 2000; Schwinghamer et al 1996; Smith & Fulton 2010; Thrush et al 1998.

itself[20], impacts of targeted fishing on predator or prey species[21] as well as whole system impacts such as regime shifts (Reid et al 2001). The approach focuses more on external influences on fish stocks; intra-ecosystem interactions; and full impact of the activity on the eco-system (FAO 2003; Garcia & Cochrane 2005; Rice et al 2005; Rice & Ridgeway 2010).

Very few of early studies of eco-systems focus on fisheries assessment and management (Smith & Fulton 2010), but the wider focus of fisheries management through EBFM, over the past decade has seen a considerable expansion in the application of ecological and ecosystem models to fisheries management issues. Examples include current approaches to ecological modeling (Walters & Martell 2004); EAF modeling (Plaganyi 2007); modeling framework on Ecopath with Ecoism (EwE) (Polovina 1984; Christensen & Walters 2004; Walters et al 1997); multi-species models, such as BORMICON (Stefansson & Palsson 1998) and GADGET (Begley & Howell 2004) and a good deal of mathematical modeling on multi-species and/or multi-fleet fisheries[22].

Though the application of eco-system models to fisheries management is almost three decades old, single-species approaches[23] (stock assessment/population dynamic) are widely accepted and used in fisheries management to inform strategic decision-making in fisheries, such as the setting of annual quota, for at least five decades (Smith & Fulton 2010). With the development of formal harvesting strategies and management procedures (Butterworth & Punt 1999), the use of stock assessment models has become deeply embedded in the whole adaptive management cycle of stock management (Smith & Fulton 2010).

[20] Bax 1985; Laevastu & Larkins 1981; Polovina 1984.
[21] For example: Beddington & May 1982; Helgason & Gislason 1979; May et al 1979; Pope 1979.
[22] For example: Anderson & Ursin 1977; Agar & Sutinen 2004; Bhat & Bhatta 2006; Chaudhuri 1986; Chaudhuri 1988; Crutchfield 1983; Eggert 1998; Fredou et al 2009; Kompas & Che 2006; Kompas et al 2010; Lleonart et al 2003; Matsuda & Abrams 2006; Pelletier et al 2009; Pope 1991; Pradhan & Chaudhuri 1999; Sparre 1991; Ruttan et al 2000; Ulrich et al 2002; Ward 1994.
[23] For example: Abaunza et al 2003; Anderson 2002; Armstrong & Skonhoft 2006; Bene et al 2001; Bjorndal et al 2004; Bolmo et al 1978; Chaudhuri & Johnson 1990; Christensen & Vestergaard 1993; Clarke et al 1992; Conard 1989; Eggert & Ulmestrand 2000; Grant et al 1981; Holland 2000; Ibaibarriaga et al 2008; Kar & Matsuda 2008; Mackinson et al 1997; McConnell & Sutinen 1979; Rettig 1987.

1.5 Fisheries management: importance of an economic perspective

Maximum Sustainable Yield (MSY)[24] is used as a benchmark management policy as well as to identify conditions and symptoms of overfishing and the stock status. The concept of MSY serves as the foundation of most biological reference points, which give decision-makers guidance in determining whether stocks are too small or fishing pressure is too large (Gulland 1983). The MSY is applicable to spawner-recruit models, surplus production models, delay-difference models, age-structured and size-structured models and so on (eg., Getz & Haight 1989; Hilborn & Walters 1992; Quinn & Deriso 1999). In the absence of information on age or length structure, surplus production models are used and the analyses are done based on effort and catch data (Chen & Andrew 1998; Hilborn & Walters 1992), which is applied in many fisheries, for example, industrial marine fisheries of Bangladesh (see, Chapter 3).

Though the level of sustainable yield and controlling catches has been considered a scientific approach to management, this approach entirely ignores economics and human behavior (Clark 2006, 2010). Effective management requires an understanding of how the fishery system is performing relative to reference points (Beddington et al 2007) and it requires understanding of how fishers are behaving in response to policy instruments. When multiple fishers compete to catch fish from a given population, each fisher maximizes his net income by continuing to fish as long as the value of his catch exceeds the cost of catching it. Arguments show that biological models are necessary, but far from sufficient for successful management (Clark 2010), hence the current widespread phenomenon of excess capacity is largely an unintended consequence of the biologically based approach to management. Managing any fishery requires both the use of mathematical modeling of population biology and an economic analysis of human behavior in fisheries.

Economic analyses allows managers to generate performance criteria to quantify management goals; to employ models to compare management strategies and policies; and to use methods to calculate performance criteria and adjust policies and regulations to better achieve target. To achieve the biological target MSY more effectively (if

[24] MSY is a sustainable harvest level, which maximizes revenue from fishing, or generates the largest value of sustainable catch in numbers or kilograms (Kompas 2005).

manager choose MSY or some other biological target), the economic analysis of fishers helps managers set incentives such that fishers no longer find race-to-fish (that generates effort-creep and overcapacity) is profitable (Grafton et al 1996; Hilborn 2007b). Efficiency, capacity and productivity analysis are the pillars of the economic approach to fisheries along with bio-economic modeling (Grafton et al 2006b). These approaches complement each other and can be used to measure both economic and biological performance; to evaluate existing strategies and tactics; to give insights as to how to improve fisheries outcomes; and guide to managers to achieve more profitable, but also sustainable fisheries.

Efficiency analysis is used to assess what factors are affecting the economic performance of the fishery and the impacts of fisheries regulation. On the other hand, productivity measures are also considered as useful indicators. For instance, declines over time in overall productivity, as measured by changes in catch per unit effort (CPUE), may be an indicator of declining fish stocks or abundance. If regulators are interested in a better understanding of fishers' performance, productivity measures can be used to provide information about stocks or abundance (Squires 1992, 1994). In the absence of stock information, fishery managers may find that the productivity performance of the fishing fleet improves over the period if the harvest increases by a proportion greater than the proportional increase in fishing effort. Managers are able to identify changing economic conditions and can separate these changes from variations in fish stocks or abundance by tracking changes in fleet productivity over time (Grafton et al 2006b).

To measure efficiency and productivity of industrial and commercial vessels Stochastic Frontier Analysis (SFA) is accepted as an appropriate technique due to the stochastic nature of harvesting marine resources (Sharma & Leung 1999). But, the SFA is limited in its application to commercial fisheries[25], though it has been extensively applied to a

[25] Campbell & Hand 1998; Coglan et al 1993; Dey et al 2000; Eggert 2001; Felthoven 2002; Fousekis & Klonaris 2003; Grafton et al 2000; Greenville et al 2006; Holloway et al 2005; Holloway & Tomberlin 2007; Hoyo et al 2004; Kirkley et al 1995; Kirkley et al 1998; Kompas et al 2004; Kompas & Che 2005; Pascoe & Coglan 2002; Pascoe et al 2001; Pascoe et al 2003a; Pascoe et al 2003b; Pascoe & Mardle 2003; Pascoe & Robinson 1996; Pascoe & Tingley 2007; Sharma & Leung 1999; Squires et al 2003; Tingley et al 2005; Tomberlin 2010; Tomberlin & Holloway 2007; Vestergaard et al 2002; Weninger 1998.

wide range of industries[26] and agricultural[27]activities. Studies[28] those employed SFA technique in fisheries, including industrial marine fisheries of Bangladesh (see Chapter 2), show many possible applications of efficiency analysis, such as the impact of input control on technical efficiency[29]. For example, in the Australian Northern Prawn Fishery (Kompas et al 2004) controls on inputs by the regulator has had the net effect of reducing technical efficiency and input substitution by the fishers raised the technical inefficiency. Such an outcome runs counter to the stated objective of the fishery regulator to both maximize economic efficiency and ensure the sustainability of the resource.

On the other hand, an analysis of the influence of individual output controls on economic efficiency in British Columbia halibut fishery (Grafton et al 2000) shows that before the introduction of individual vessel quota (IVQ), there was a decline in efficiency for both small and large vessels. After the transferability of IVQ, fishers were able to adjust their harvest to the appropriate scale of harvest and adjust the mix of inputs in a better way to take advantage of the increase in the fishing season. As a result, both short run technical efficiency and economic efficiency increased for small and large vessels (Grafton et al 2000). An examination of how vessels, gear, skipper and crew characteristics affect technical efficiency in Malaysian artisanal gill net fishery shows high levels of technical efficiency and few benefits from improvements in gear and equipment (Squires et al 2003). All this efficiency analysis shows the factors affecting the economic performance of the fishery and the impacts of fisheries regulations. If an effective management structure exists that prevents biological and economic overexploitation, improvements of efficiency by vessels are desirable. Changes in efficiency of vessels are also strongly influenced by regulations. Imposing

[26] For example: manufacturing (Harris 1993; Sheehan 1997), steel production (Wu 1996).

[27] For example: dairy farms (Battese & Coelli 1988; Hallam & Machado 1996; Jaforullah & Devlin 1996; Kompas & Che 2004) and crop farms (Bravo-Ureta & Pinherio 1993; Heshmati & Kumbhakar 1997; Kompas 2002; Neff et al 1993).

[28] The SFA was first employed in the mid-Atlantic sea scallop fishery (Kirkley et al 1995, 1998) followed by longline fishery in Hawaii (Sharma & Leung 1999), mid-Atlantic surf clam and ocean quahog fishery (Weninger 2001), Dutch beam trawler fishery (Pascoe et al 2001), English Channel fishery (Pascoe & Coglan 2002), British Columbia halibut fishery (Grafton et al 2000), Malaysian artisanal gill net fishery (Squires et al 2003); Australia's banana prawn fishery (Kompas et al 2004), New South Wales, Australia ocean prawn trawl fishery (Greenville et al 2006) and many other fisheries.

[29] '…Technical efficiency is usually what fishery managers refer to when making efficiency comparisons across vessels, or over time. An input-oriented way of defining technical efficiency is the minimum amount of inputs required to produce a given level of output. In many fisheries, fishing vessels are not technically efficient because they use too many inputs, or, are overcapitalized in the sense that a lower level of input (often measured in number of vessels) could be used to catch the same total harvest. Technical efficiency may surface for many reasons, but, a major cause is input controls that fail to prevent effort creep due to input substitution….' (Grafton et al 2006b).

restrictions on what gear can be used by fishers affects the ability of vessels to harvest fish, and thus their efficiency. Efficiency in fisheries is not possible without appropriate governance and management (Grafton et al 2006b).

In the absence of any effective controls or management a fishery will converge to a bio-economic equilibrium[30]. In many fisheries, the bio- economic equilibrium coincides with a lower fish stock than that which maximizes the sustained yield and will always be at a level where fishing effort exceeds that which maximizes the economic surplus or economic profit from fishing. To achieve maximum economic efficiency from a fishery correct and effective management targets are important. A benchmark to compare current economic performances in fisheries with potential economic performances is explained by Maximum Economic Yield (MEY)[31]. MEY is generated by the management structure, stock level, nature and extent of fishing effort, which depends on a combination of biological and economic factors.

Maximizing economic efficiency in fisheries requires setting appropriate levels of catch and effort levels. To hold MEY, vessels efficiency must be maximized. For example, vessel level efficiency studies both on the Australian Northern prawn fishery (NPF) and the Australian South East trawl fishery (SETF) show overcapitalization (Kompas et al 2009), where NPF introduced a MEY target, but the instrument used in the fishery (input control) generates considerable efficiency losses. On the other hand, in the SETF rights-based instrument, the Individual Transferrable Quota (ITQ) is used to ensure vessel-level efficiency, which is easily transferrable, but doesn't employ an appropriate target. So, correct and effective management targets are important to achieve maximum economic efficiency from a fishery. In the absence of correct management targets, inefficient fisheries, such as industrial marine fisheries of Bangladesh (see Chapter 4) suffer overcapacity, excess fishing capacity and low profits and hence fisheries become both biologically over-exploited and economically unprofitable. Efficient management of fisheries protects stocks, guarantees sustainability and assures correct allocation of resources in a way that maximizes the returns from fishing (Grafton et al 2006b; Kompas 2005).

[30] In the bio-economic equilibrium, there is no economic surplus.
[31] MEY is a sustainable catch or effort level, which creates the largest difference between (discounted) total revenues and the total cost of fishing (Kompas 2005).

1.6 Structure of the thesis

This thesis is a combination of three core essays (Chapter 2-4) on management of industrial marine fisheries of Bangladesh followed by a concluding essay (Chapter 5) on the impact of traditional command and control approaches to marine fisheries management with evidence of industrial marine fisheries of Bangladesh. The first core essay (Chapter 2) investigates the effect of input control on vessels' performances of the industrial marine fisheries of Bangladesh and the vessels' performance is measured in term of technical efficiency and productivity. The study shows that vessels are producing below the maximum level of output and are too small in their scale of operation. It also shows input control induces vessels operators to intensify usage of unregulated inputs. The study shows that the input control that is employed in industrial marine fisheries in Bangladesh fails to increase vessels efficiency and productivity. Hence, an alternative management strategy is needed to increase technical efficiency and productivity of both industrial marine shrimp and fish fisheries of Bangladesh.

The second core essay (Chapter 3) estimates biological reference points of single-species and single-fleet industrial marine fisheries of Bangladesh in order to find out the current status of the industrial marine fisheries. The study shows that the shrimp stock of the industrial marine fisheries is over-exploited and the fall in catch per unit effort (CPUE) over time of the industrial marine shrimp fishery is due to the fall in stock size. On the other hand, the fish stock of the industrial marine fisheries is under-exploited and the fall in CPUE over time of the industrial marine fish fishery is due to inadequate knowledge and information on the availability of the sizes of different fish stocks and lack of technological developments for harvesting the new resources. The study also shows that to maintain steady-state equilibrium and adequate growth rate of both shrimp and fish, fishing patterns need to be modified. The study also indicates that the current management strategy fails to increase the level of high-valued shrimp stocks and to increase the catch level of the low-valued stocks. Hence, an alternative management strategy is needed for both industrial marine shrimp and fish fisheries of Bangladesh.

The third core essay (Chapter 4) measures the economic performance of the single-species and single-fleet industrial marine fisheries of Bangladesh. The study shows that excessive use of efforts makes both shrimp and fish fisheries economically inefficient in the form of low stock biomass and profit. The study also shows that reductions in the number of vessels in both shrimp and fish fleets are needed. The study indicates that the MEY is the best management target compare to the MSY to improve the economic efficiency of both industrial marine shrimp and fish fisheries of Bangladesh. Based on the findings of these three core essays, this research confirms that in the absence of correct management targets and property rights, the open access Bangladesh industrial marine fisheries becomes inefficient and overcapitalized. The fishery also suffers overcapacity and is economically unprofitable. This research also confirms that the industrial shrimp fishery is biologically over-exploited.

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Chapter 2

Technical efficiency and productivity of the industrial marine fisheries of Bangladesh

2.1 Introduction

In natural resource-based industries, such as fishing, the performance of vessels is important to policy decisions regarding fisheries management and to prevent overfishing. It is often argued that fisheries managers are more concerned with biological assessment of the marine resource rather the economic performances of vessels. Literature shows that the knowledge of the productive performance of individual vessels relative to the available technology and its interaction with other socio-economic factors are important consideration when formulating appropriate regulation (Sharma & Leung 1999). In order to maximize social benefit from the marine fisheries, efficient utilization of resources associated with fishery production and sustainable management of resource stocks are also important.

To prevent overfishing, fisheries managers often employ input controls under the assumption that it restricts input use and indirectly leads to a level of output being achieved. Input control normally controls the use of those inputs that are readily measureable, for example vessel size, engine power, gear use and fishing days (Pascoe & Coglan 2002). Studies show that input control fails to reduce fishing pressure (Greenville et al 2006). Arguments show that control placed on the use of one input induces fishers to overuse unregulated inputs in production process. In many cases fishers substitute inputs with unregulated inputs (Kompas et al 2004). Studies show that input control fails to produce maximum levels of output in most fisheries. So, efficiency and productivity measures are important to assess a vessel's performance and in determining the effects of fisheries policies.

Due to the stochastic nature of harvesting marine resources, Stochastic Frontier Analysis (SFA) is accepted as an appropriate technique to measure efficiency and productivity of industrial and commercial vessels (Sharma & Leung 1999). The SFA has been extensively applied to a wide range of industries[32] and agricultural[33] activities, but, is limited in its application to commercial fisheries[34]. The SFA was first employed in the mid-Atlantic sea scallop fishery (Kirkley et al 1995, 1998) followed by longline fishery in Hawaii (Sharma & Leung 1999), mid-Atlantic surf clam and ocean quahog fishery (Weninger 2001), Dutch beam trawler fishery (Pascoe et al 2001), English Channel fishery (Pascoe & Coglan 2002), British Columbia halibut fishery (Grafton et al 2000), Australia's banana prawn fishery (Kompas et al 2004) and New South Wales, Australia ocean prawn trawl fishery (Greenville et al 2006). Sharma & Leung (1999) adopted the methodological coherent approach to estimate the efficiency of longline fishery in Hawaii that requires a simultaneous estimation of production frontier model and an inefficiency effect model by maximum likelihood estimation (Coelli et al 2005; Battese & Coelli 1995; Huang & Liu 1994).

The objective of this study is to determine the effect of input control on vessels' performances in the industrial marine fisheries of Bangladesh and the vessels' performance of this study is measured in terms of efficiency and productivity. This is the first kind of study to measure performance of vessels in the industrial marine fisheries of Bangladesh. A panel data set for the period 2001-2007 for Translog production function and technical efficiency effect model is used to measure efficiency; and Total Factor Productivity (TFP) is used to measure productivity. Theoretical consistencies of translog production function for vessel, output elasticity associated with all inputs, elasticity of scale and marginal productivity of all inputs are examined in this study. Technical efficiency, technical progress and scale change are also estimated to find out the sources of productivity. The study shows that vessels are producing below the maximum level of output and are too small in their scale of operation. It also shows input control induces vessels operators to intensify use of unregulated inputs.

[32] For example: manufacturing (Harris 1993; Sheehan 1997), steel production (Wu 1996).
[33] For example: dairy farms (Battese & Coelli 1988; Hallam & Machado 1996; Jaforullah & Devlin 1996; Kompas & Che 2004) and crop farms (Bravo-Ureta & Pinherio 1993; Heshmati & Kumbhakar 1997; Kompas 2002; Neff et al 1993).
[34] Campbell & Hand 1998; Coglan et al 1999; Dey et al 2000; Eggert 2001; Felthoven 2002; Fousekis & Klonaris 2003; Grafton et al 2000; Greenville et al 2006; Holloway et al 2005; Holloway & Tomberlin 2007; Hoyo et al 2004; Kirkley et al 1995; Kirkley et al 1998; Kompas et al 2004; Kompas & Che 2005; Pascoe & Coglan 2002; Pascoe et al 2001; Pascoe et al 2003a; Pascoe et al 2003b; Pascoe & Mardle 2003; Pascoe & Robinson 1996; Pascoe & Tingley 2007; Sharma & Leung 1999; Squires et al 2003; Tingley et al 2005; Tomberlin 2010; Tomberlin & Holloway 2007; Vestergaard et al 2002; Weninger 1998.

The remainder of this chapter is divided into five sections. Section 2.2 provides a theoretical framework followed by data sources and variables in Section 2.3. The econometric specification is described in Section 2.4. Section 2.5 presents results and discussion. Section 2.6 offers conclusions.

2.2 Theoretical framework

Productivity and productivity changes are important indicators of performance measurement of firms and vessels. To compare performance of firms in a given point in time, measures of productivity are used, and to show movement in productivity performance of firms or an industry over time, measure of productivity change is used. A more suitable performance measurement and comparisons across firms and vessels for a given firm or vessel over time is the Total Factor Productivity (TFP), which can be measured either using a top-down[35] approach or bottom-up[36] approach (Coelli et al 2005).

Total factor productivity can be decomposed into three or four components. In a non-constant returns to scale production system, the commonly used sources of productivity change are technical change, technical efficiency change, scale change and allocative efficiency change. Allocative efficiency changes can be used when input prices paid by the producers are known. Balk (2001) identifies another source of productivity, which is known as output/input mix effect (OME/IME). OME/IME measures the effect of changes in the composition of the output and input over different periods and can be used for multi-output and multi-input firms, but, is not commonly discussed in the literature. In the absence of price data, efficiency and productivity measurement are restricted to the measurement of technical efficiency, scale change and technical change (Coelli et al 2005). In this study, prices paid for the inputs are unknown hence three sources of productivity growth of the vessels are used: technical change, technical efficiency change and scale change.

Technical change (TC) is an important source of productivity growth that results from shift in the production technology, while the technical efficiency change (TEC) is

[35] Such as Hicks-Moorsteen approach, Profitability approach, Caves-Christensen-Diewert (CCD) approach and Component-based approach of TFP.

[36] The approach that identifies sources of productivity changes and constructs a measure of the growth in TFP.

another important source of productivity that comes from improvement of technical efficiency in the firm/vessel's ability to use the available technology. Changes in technical efficiency define the rate at which producers move closer to, or, further away from the production function.

Efficiency measurement is first introduced by Farrell (1957) based on the work done by Debreu (1951) and Koopmans (1951) to define a simple measure of firm efficiency. The efficiency of a firm depends on two components, namely, technical efficiency and allocative efficiency. Technical efficiency shows the ability of a firm to obtain maximum output from a given set of inputs and the allocative efficiency measures the ability of a firm to use the inputs in optimal proportions, given their respective prices and production technology (Kumbhakar & Lovell 2000). The combination of these two efficiency measures provides the economic efficiency of a firm. As prices paid for the inputs are unknown, efficiency measure in this study refers to technical efficiency and could be measured with both parametric and non-parametric functions.

Another important source of productivity growth is scale change (SC) that originates from improvements in the scale of operations of the firm or vessel, which moves towards a technologically optimum scale of operations. Arguments show that TFP may produce biased measures if the scale changes do not capture the measure of productivity changes (Coelli et al 2005). There have been several attempts to measure scale change and its influence on productivity change over time. Fare et al (1998) define scale change and use it in deriving decomposition of productivity changes over time. A formal framework for scale change and the role of scale change in productivity changes are also provided by Balk (2001) and show a comparison of earlier literatures[37] in decomposing productivity change into efficiency change, technical change and scale change. Another formal measure of scale change is proposed by Orea (2002). He suggests that the scale issue can be addressed using Denney et al (1981) and can be measured by using output elasticity of inputs and total elasticity of production/elasticity of scale.

A stochastic production frontier is used in this study to measure technical efficiency. Stochastic frontier analysis assumes a given functional form for the relationship

[37] Fare et al (1994), Ray & Desli (1997), Grifell-Tatje & Lovell (1999), Wheelock & Wilson (1999), Zofio & Lovell (1999).

between input and output. Stochastic production frontiers were developed by Aigner et al (1977) and by Meeusen & van den Broeck (1977). The specification of these authors allow for a non-negative random component in the error term to generate a measure of technical inefficiency, or the ratio of actual to expected maximum output, given inputs and the existing technology. The idea can be applied to both cross section data (Kalirajan & Shand 1994) and panel data (Battese & Coelli 1995; Coelli et al 2005).

The stochastic frontier production function model for cross section data can be written as:

$$lnY_i = X_i'\beta + v_i - u_i \tag{2.1}$$

Where Y_i represents the output of the i-th firm; X_i' is a $(1{\times}k)$ vector containing the logarithms of inputs; β is a $(k{\times}1)$ vector of unknown parameters in the model; v_i is a symmetric random error to account for statistical noise, which can be positive or negative, and u_i is a non-negative random variable associated with technical inefficiency. Adding a subscript t to represent time, the panel data form of the stochastic frontier production function model of the Equation 2.1 can be written as:

$$lnY_{it} = X_{it}'\beta + v_{it} - u_{it} \tag{2.2}$$

Panel data contains more observations than cross-sectional data and can give efficient estimators of the unknown parameters and more efficient predictors of technical efficiency.

An appropriate functional form, either first-order flexible[38] or second-order flexible[39], is normally used to estimate stochastic production frontier. To confirm appropriate functional form the parameters of different models can be estimated by Maximum Likelihood Estimation (MLE) and then these models can be compared using a generalized likelihood ratio test. To use the maximum likelihood principle to estimate the parameters of the model and in order to identify the random effects and technical

[38] A first-order flexible functional form has enough parameters to provide a first-order differential approximation to an arbitrary function at a single point. For example: Cobb-Douglas.

[39] A second-order flexible form has enough parameters to provide a second-order approximation. For example: Translog.

inefficiency effects in the model, an assumption concerning the distribution of the error terms is important (Coelli et al 2005).

The maximum likelihood approach involves making stronger distributional assumptions concerning the u_{it}. Different distributional assumptions of u_{it} are commonly used, such as, a half-normal distribution truncated with zero mean and variance σ_u^2, $u_i \sim iidN^+(0,\sigma_u^2)$ (Aigner et al 1977; Pit & Lee 1981) and a truncated normal distribution with mean μ and variance σ_u^2, $u_i \sim iidN^+(\mu,\sigma_u^2)$ (Stevenson 1980; Battese & Coelli 1988). A gamma distribution with mean λ and degrees of freedom m , $u_i \sim iidG(\lambda,m)$ (Green 1990; Coelli et al 2005) and an exponential distribution with mean λ, $u_i \sim iidG(\lambda,0)$ (Coelli et al 2005) are also used in some studies. The log-likelihood functions on different distributions, such as, truncated normal, gamma and an exponential distribution for different models can also be found in Kumbhakar & Lovell (2000).

A time-invariant and a time-varying structure of u_{it} are also commonly used in the literature. A time-invariant structure of u_{it} takes the form of $u_{it} = u_i$ and u_i is treated as either a fixed parameter or a random variable and these models are usually known as fixed effects models and random effects model. Fixed effects models can be estimated in a standard regression framework and random effects model can be estimated with either least squares or maximum likelihood techniques (Coelli et al 2005). A time-varying technical inefficiency takes the form of $u_{it} = f(t).u_t$ where $f(t)$ is a function that determines how technical efficiency varies over time and two functional forms of $f(t)$ are commonly used, such as, $f(t) = \left[1 + e^{\alpha t + \beta t^2}\right]^{-1}$ (Kumbhakar 1990) and $f(t) = e^{[\eta(t-T)]}$(Battese & Coelli 1995).

In this study, a Translog functional form of a stochastic production function model is used, which can be written as:

$$Y_{it} = \exp\left(\beta_0 + \sum_{n=1}^{N}\beta_{nit}\ln X_{nit} + \frac{1}{2}\sum_{n=1}^{N}\sum_{m=1}^{N}\beta_{nm}\ln X_{nit}.\ln X_{mit} + v_{it} - u_{it}\right) \tag{2.3}$$

In the model, Y_{it} represents the production of the i-th vessel and *i=1,2,3, n* at time t and *t= 1,2, T*; X_{it} a $(1\times k)$ vector of inputs used in production; β a $(k\times 1)$ vector of unknown parameters to be estimated; the error term v_{it} is assumed to be independently and identically distributed as $N(0,\sigma_v^2)$ and captures random variation in output due to factors beyond the control of vessels, which can be positive or negative; the error term u_{it} a non-negative random variable and captures vessel-specific technical inefficiency. u_{it} is obtained by a non-negative truncation of $N(z_{it}\delta,\sigma_u^2)$, which allows the inefficiency effects in the frontier model to vary with z_{it} a $(1\times m)$ vector of vessel-specific explanatory variables; and δ a $(m\times 1)$ vector of unknown coefficients to be estimated. Thus, u_{it} in the production model of this study can be specified as:

$$u_{it} = z_{it}\delta + w_{it} \tag{2.4}$$

Where, w_{it} a random variable that is assumed to be independently and identically distributed and $u_{it} \geq 0$. The condition $u_{it} \geq 0$ guarantees that all observations lie on or beneath the stochastic production frontier. Vessel specific characteristics can also be picked up by adding vessel dummy variables in u_{it}.

The technical efficiency (TE) of the *i*-th vessel in the *t*-th period can be defined as:

$$TE = \frac{E(Y_{it}|u_{it}, X_{it})}{E(Y_{it}|u_{it} = 0, X_{it})} = e^{-u_{it}} = e^{-z_{it}\delta - w_{it}} \tag{2.5}$$

and must have a value between zero and one. The measure of TE is based on the conditional expectation given by Equation 2.5, given the values of $v_{it} - u_{it}$ evaluated at the maximum likelihood estimates of the parameters in the model, where the expected maximum value of Y_{it} is conditional on $u_{it} = 0$.

Efficiency can be calculated for each individual vessel per year by:

$$E\left[e^{u_i}\left|v_i+u_i\right.\right]=\frac{1-\phi\left(\dfrac{\sigma_a+\gamma(v_i+u_i)}{\sigma_a}\right)}{1-\phi\left(\dfrac{\gamma(v_i+u_i)}{\sigma_a}\right)}e^{\gamma(v_i+u_i)+\frac{\sigma_a^2}{2}} \tag{2.6}$$

for $\sigma_a=\sqrt{\gamma(1-\gamma)\sigma^2}$ and $\phi(.)$ the density function of a standard normal variable (Battese & Coelli 1988; Kompas et al 2004).

The likelihood function is expressed in terms of the variance parameters (a normal distribution with some restrictions) (Coelli et al 2005). The variance terms are parameterized by Battese & Corra (1977) by replacing σ_v^2 and σ_u^2 with $\sigma^2=\sigma_v^2+\sigma_u^2$ and $\gamma=\frac{\sigma_u^2}{\sigma_v^2+\sigma_u^2}$. A value of γ close to zero denotes that deviation from the frontier is due entirely to noise and then the expected value of the TE score is one, while a value of γ close to one would indicate that all deviations are due to inefficiency. So $\gamma=0$ implies there are no deviations in output due to inefficiency; $\gamma=1$ implies deviations in output are due to technical inefficiency effects and $0<\gamma<1$ implies deviations in output are due to both noise and technical inefficiency.

A trend can also be included in the Equation 2.1 to capture time-variant effects and the time trend in Translog model allows non-neutral technical change and technological change effect to increase or decrease with time.

A firm or vessel can be technically efficient, but the scale of operation of the firm may not be optimal. A firm may be either too small in its scale of operation and fall within the increasing returns to scale (IRS) of the production function or, too large and may operate within the decreasing returns to scale (DRS). In both cases efficiency of the firm can be improved by changing their scale of operations. A firm is automatically scale efficient if its production technology shows constant returns to scale (CRS) (Coelli et al 2005). A widely-used measure of returns to scale is the elasticity of scale or, total elasticity of production, which is considered in this study to measure scale of operation of the vessels. Thus, the elasticity of scale of the vessels can be calculated as:

$$\varepsilon(X) = \sum_{n=1}^{N} \varepsilon_n(X_n) \tag{2.7}$$

Where, $\varepsilon_n(X_n) = \sum\left(\beta_n + \sum_{m=1}^{N} \beta_{nm}.\ln X_{mit}\right)$ is the output elasticity with respect to n inputs and n = *1,2,3, N*.

Using output elasticity, the marginal product of $n-$th input (n = *1,2,3,N*) at mean values of output and relevant input variables can be calculated as:

$$f_n = \frac{\partial Y}{\partial X_n} = \varepsilon_n(X_n).\frac{\overline{Y}}{\overline{X_n}} \tag{2.8}$$

The total factor productivity (TFP) of the individual vessels per year can be calculated as:

$$TFP_{it,t-1} = TC_{it,t-1} + TEC_{it,t-1} + SC_{it,t-1} \tag{2.9}$$

Where, $TC_{it,t-1} = e^{\frac{1}{2}(TP_{it}+TP_{it-1})}$ is the technical change, and the technological progress (TP) for t and $t-1$ period can be calculated from the production function as, $TP_i = \beta_t + 2\beta_{tt}.t + \sum_{n=1}^{N} \beta_{tn}.\ln X_{ni}$; $TEC_{it,t-1} = \frac{TE_{it}}{TE_{it-1}}$ is the technical efficiency change and for t and $t-1$ period technical efficiency change can be calculated from technical inefficiency effect model as, $TE_i = e^{-z_i\delta - w_i}$; and $SC_{it,t-1} = e^{\{\varepsilon(X)-1\}\sum_{n=1}^{3}\left(\frac{\varepsilon_n(X_n)}{\varepsilon(X)}\right).(\ln X_{nit} - \ln X_{nit-1})}$ is the scale change (Greenville et al 2006) and for t and $t-1$ period scale change can be calculated using Equation 2.7.

2.3 Data and variables

All data used in this study is collected mainly from fishing log books data, license renewals data and other office based records from the Marine Fisheries Department (MFD) under Department of Fishery (DoF) of Bangladesh.

The industrial/commercial fishing in the marine waters of Bangladesh was officially introduced in 1984 with a large number of imported second hand trawlers and vessels. Industrial fishing vessels of Bangladesh are divided into two broad categories: shrimp and fish, and these fisheries are commonly known as industrial marine fisheries. Vessels in the shrimp fleet are double-rigged vessels, fitted with two side beams from which two shrimp-trawl nets are simultaneously operated. A standard shrimp vessel is made of a steel hull and mesh size of the net at the cod-end is 45mm. Shrimp vessels target three principal species; *Penaeus monodon* (tiger shrimp), *Penaeus indicus* (white shrimp), *Metapenaeus monodon* (brown shrimp) as well as pink shrimp. Shrimp trawls occur beyond 40 metres depth within the EEZ of Bangladesh to catch shrimp and fish.

On the other hand, vessels in fish fleet are stern vessels with a single-rigged trawl-net operated behind the vessels and these vessels are smaller than shrimp vessels (MFD 2009). These vessels generally have both wooden and steel hulls and the mesh size of the net at the cod-end is 60mm. Fish vessels target fin fish, demersal white fish and mid water fish. Fish trawls occur in four different fishing areas. Traditional fish trawls occur beyond 40 metres depth at high tide to catch fin fish and shrimp; modern fish trawls occur between 40 and 100 metres depth to catch fin fish; demersal trawls occur between 100-200 metres depth to target demersal white fish and mid water trawls occur beyond 40 metres depth to catch mid water fish.

According to the Marine Fisheries Department (MFD) of Bangladesh, the management system for shrimp vessels is closed season, licensing and input control. On the other hand, the management system for fish vessels is licensing and input control. License fees are based on Gross Tonnage (GT) of the vessels. Each year all vessels have to renew their license with the specific amount of fees fixed by the Government. The license fee of shrimp vessels varies from US $15 (for 0-10 GT) to US $1090 (for 600 and above GT) and fish vessels vary from US $10 (for 0-10 GT) to US $727 (for 600 and above GT). Input control allows replacement of vessels and input restriction is imposed on vessel size, gross tonnage, engine size, mesh size and fishing days. Input restriction allows vessels to fish at least 150 days per year (MFD 2009).

The management of the industrial marine fisheries is governed by the Marine Fisheries Ordinance 1983, the Marine Fisheries Rules 1983 and the Fish and Fish Products (Inspection and Quality Control) Ordinance 1983. The Marine Fisheries Ordinance

1983 regulates the management, conservation and development of marine fisheries. The Marine Fisheries Rules 1983 regulates the issuance and conditions of fishing license, license conditions, types of fishing gear, mesh size, fishing area and fishing days. The Fish and Fish Products (Inspection and Quality Control) Ordinance 1983 regulates the issuance of licenses to ensure food safety requirements for fish products and to increase the quality of catch by all vessels.

Shrimp and fish vessels use different technologies in different target areas and target different species. Both shrimp and fish vessels have considerable heterogeneity in terms of total value of catch, engine power, total crew, fishing days, gear length, vessel age, storage capacity, number of owner/s, cost of quality control and market orientation.

The total number of vessels of the industrial marine fisheries of Bangladesh is increasing over time due to policy shifts, first in 2000 and then in 2004 (Table 2.1).

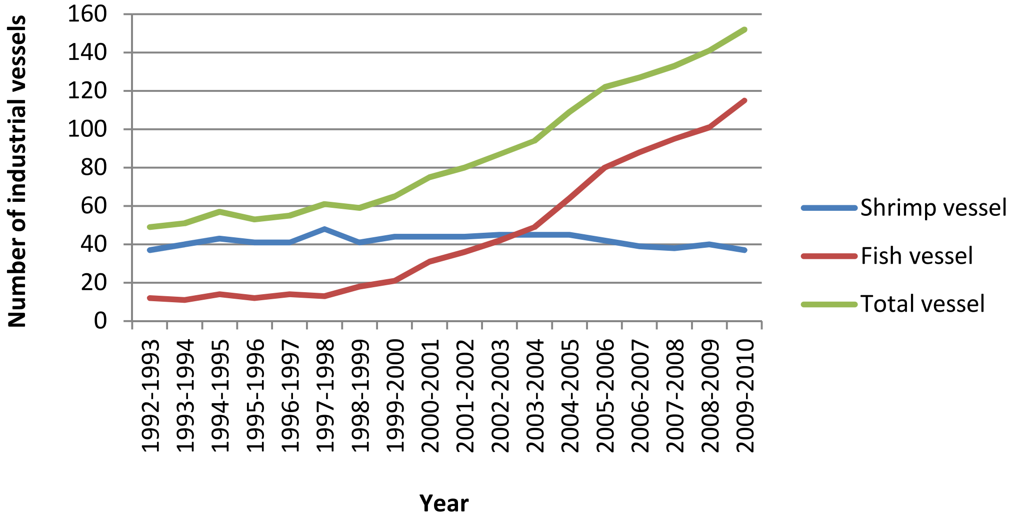
Table 2.1 **Number of vessels, total catch (tonnes) and catch per vessels (1992-2011)**

	Period	Maximum	Minimum	Average	Difference between period	↑ or ↓
Number of vessels	1992-1996	57	49	53	-	-
	1996-2001	75	55	63	11	↑
	2001-2006	122	80	98	35	↑
	2006-2011	158	127	142	44	↑
Total catch (tonnes)	1992-1996	12454	11715	12089	-	-
	1996-2001	23901	13564	16972	4883	↑
	2001-2006	34114	25165	30785	13813	↑
	2006-2011	41643	34159	36161	5376	↑
Catch per vessel (tonnes)	1992-1996	250	206	231	-	-
	1996-2001	319	247	267	36	↑
	2001-2006	347	279	315	48	↑
	2006-2011	279	225	255	-60	↓

Source: Author's calculation based on 'Fisheries Statistics, Department of Fishery, Ministry of Fisheries and Animal Resources, various editions, Dhaka'.

The average number of industrial vessels for every five years of data between 1992 and 2011 in Table 2.1 shows a dramatic increase in average number of vessels during 1996-2011 and consequently both catch per vessel and the volume of average total catch show a significant drop between 2006 and 2011. The yearly data also shows a sharp increase in the number of industrial vessels from 1996 onwards (Figure 2.1). Figure 2.1 shows that the total number of shrimp vessels is almost constant over time, but, there is a sharp increase in the number of fish vessels from 1996 onwards and hence a sharp increase in total industrial vessels.

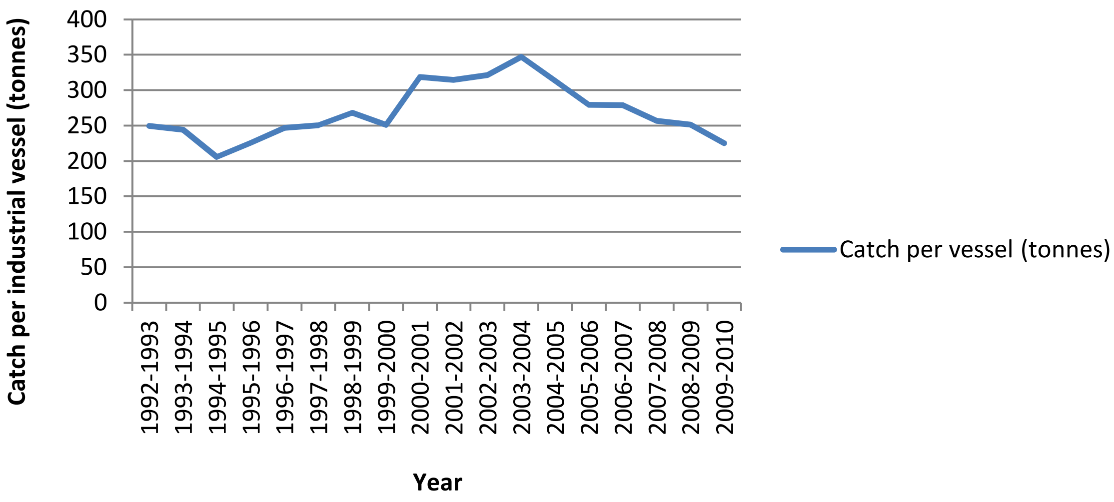
Figure 2.1 **Number of industrial vessels over time**



Source: Author's calculation based on 'Fisheries Statistics, Department of Fishery, Ministry of Fisheries and Animal Resources, various editions, Dhaka'.

The yearly data in Figure 2.2 shows during 1995-2003, an increasing trend along with a sharp drop in 2000 in catch per vessels (tonnes) with a sharp increase in volume of industrial vessels from 1996 to onwards (Figure 2.1), but, a sharp decline in catch per vessel is reported from 2004 to onwards (Figure 2.2).

Figure 2.2 **Catch per industrial vessel over time**



Source: Author's calculation based on 'Fisheries Statistics, Department of Fishery, Ministry of Fisheries and Animal Resources, various editions, Dhaka'.

The study investigates vessels' performances in terms of efficiency and productivity during 2001-2007 for both shrimp and fish vessels separately[40]. The average total number of shrimp and fish vessels operated during the period 2001-2007 is 43 and 56, respectively (Table 2.2).

Table 2.2 **Number of vessels over time**

Year	Shrimp	Fish	Total
2001	44	31	75
2002	44	36	80
2003	45	42	87
2004	45	49	94
2005	45	64	109
2006	42	80	122
2007	39	88	127
Average	43	56	99

Source: 'Fisheries Statistics, Department of Fishery, Ministry of Fisheries and Animal Resources, various editions, Dhaka'.

Of them, only 18 shrimp vessels and 8 fish vessels are selected for this study. For instance, Coglan et al (1999) used only 63 boats out of 457 boats and Kirkley et al (1995, 1998) considered only 10 boats in their analyses. The first study considered only those vessels which had observations for at least 4 months a year in at least 3 of the 4 years. The later study considered only those boats which had a long and consistent time series.

In this study, the presence of outliers in data is addressed by dropping the invalid observations. Vessels with few or no observations and vessels that operated for only a few years are excluded and unity-based normalization is done for all variables for both shrimp and fish vessels. As a result, a balanced panel data set for both vessels over the period 2001-2007 is used to compare different vessels in the different time period. Thus, the total number of observations for shrimp and fish vessels is 126 and 56, respectively. Considering all heterogeneity, two separate production functions with two inefficiency effects models are used in this study for both shrimp and fish vessels.

[40] The status of the fishery data up to 2011 (such as: number of vessels, total catch) is available in the published office documents and in the website. On the other hand, input data that is used in this study collected during field work in early 2009 from log books and license renewal papers. During that period input data is available up to 2007. As the data, after 2007 are not available in any published documents or in the web site, collecting more recent data through field visit is time consuming. Hence, more recent data is not used.

2.3.1 Variables in production function

Shrimp and fish vessels both produce two outputs, shrimp and fish, using the same set of inputs. In most studies in fishery, when single-species are examined a landed weight is considered an output measure and value of catch is considered when multiple species are harvested. For example, value per trip is used for a mixed Hawaiian longline fishery (Sharma & Leung 1999) and value of catch per month is used in an analysis of English Channel demersal trawl fishery (Pascoe & Coglan 2002). As Bangladesh's industrial marine fisheries is producing both shrimp and fish by both shrimp and fish vessels, the aggregate value of total catch is used in this study for the output variable in both production functions. Data for the amount of shrimp and fish catch (tonnes per year) is collected from fisheries log books of MFD under DoF and is converted into values (thousand US dollars per year) using shrimp and fish prices. Both shrimp and fish prices are calculated using value of export (*taka*) and quantity of export (tonnes) of both shrimp and fish. Value and quantity of export are collected from various editions of the Fisheries Statistical Year Book published by DoF. Shrimp and fish prices measured in *taka* and converted into US dollars using the Annual Nominal Exchange Rate (ANER) are collected from Bangladesh Economic Review (Ministry of Finance (MoF) 2012). A common price for all vessels for both shrimp and fish is used. The price of shrimp and fish are different and varies between 2001 and 2007. The total value of catch per shrimp vessel varies between US $110,000 and US $2125,000 with an average of US $943,000 per year and the standard deviation is US $511,400 per year. On the other hand, the total value of catch per fish vessel varies between US $435,000 and US $2459,000 with an average of US $1391,000 per year and the standard deviation is US $510,890 per year. Data used in this study shows that the total value of catch of fish vessels is much higher than that of shrimp vessels.

Different studies use different choices of input variables to explain production frontier and the choice of input variables differs based on characteristics of the fishery. For example, crew size, trip length and the cost of other variable inputs, such as fuel, bait, ice, etc are used by Sharma & Leung (1999) in longline fishery; crew size, days at sea, gear, and size of boats are considered by Kirkley et al (1995, 1998) in Atlantic Scallop fishery and engine power, number of trip each month, gear, and size of boats are used by Pascoe & Coglan (2002) in English Channel demersal trawl fishery. As both shrimp and fish vessels in Bangladesh's industrial marine fisheries are using the same set of inputs, engine power, crew size and fishing days are considered as input variables for both production functions in this study. All input data used in both production functions is collected from MFD.

Engine power is considered a fixed input for both production functions and measured in Brake Horse Power (BHP). For both shrimp and fish vessels, engine power varies between 450 and 960 BHP with an average of 664 BHP and a standard deviation of 168 BHP for shrimp vessels and an average of 694 BHP and a standard deviation of 205 BHP for fish vessels. Data use in this study shows that the average of engine power of fish vessels is a little higher than that of shrimp vessels.

Vessel specific total crew data is used in this study as quality/category specific crew size is not available. For both shrimp and fish vessels, crew size is fixed between 2001 and 2007 for all vessels, but, varies between vessels. The size of crew for shrimp vessels varies between 26 and 41 with an average of 32 and the standard deviation is 6. On the other hand, the size of crew for fish vessels varies between 24 and 41 with an average of 30 and the standard deviation is 6. Data use in this study shows that the average of the size of crew of shrimp vessels is a little higher than that of fish vessels.

Fishing days are considered as a variable input for both production functions and measured in days per year. For shrimp vessels, fishing days per year vary between 14 and 246 with an average of 175 days per year and the standard deviation is 43 days. On the other hand, fishing days for fish vessels per year varies between 120 and 254 with an average of 169 days per year and the standard deviation is 28 days. Data use in this study shows that the average of fishing days per year of shrimp vessels is a little higher than that of fish vessels. According to the Marine Fisheries Rules, freezer vessels can fish 20-25 days per trip and non-freezer vessels can fish 10-12 days per trip (MFD 2009). All shrimp vessels are freezer vessels, but fish vessels are both freezer and non-freezer vessels.

A time trend is used to capture technical change (such as technological innovation, changes in fishing patterns and practices and so forth) over time on harvest. A binary variable for the year 2004 is used in the production function to capture change in regulation.

2.3.2 Variables in inefficiency model

Vessel specific factors including vessel age, gear length, market orientation and ownership are considered in the inefficiency effect models for both shrimp and fish vessels. In addition, storage capacity, quality control costs and vessel specific dummy variables are used in the inefficiency effect model for shrimp vessels. All data use in this model is collected from MFD.

Storage capacity shows the size of vessels. It is measured in tonnes and varies between 41 and 181 tonnes for shrimp vessels with an average of 76 tonnes and a standard deviation of 33 tonnes. On the other hand, storage capacity for fish vessels varies between 54 and 119 tonnes with an average of 90 tonnes and a standard deviation of 24 tonnes. Data use in this study shows fish vessels have higher storage capacity than those of shrimp vessels, that is, fish vessels are larger than shrimp vessels.

The quality control variable used in this study is a sum of expenditure on hygiene and quality control; and quality and laboratory certificates and the average cost per year for shrimp vessels is US $6,000 per and for fish vessels is US $174. The cost varies for shrimp vessels between US $200 and US $16,000 per year with a standard deviation of US $4,000 per year and for fish vessels between US $150 and US $195 with a standard deviation of US $14 per year. All expenditure is calculated in *taka* and converted into US dollars using the annual exchange rate. The quality control cost per year for shrimp vessels is higher than that of fish vessels. Most shrimp vessels exploit high-valued stocks and are export-oriented vessels that incur quality control costs to meet the conditions of foreign buyers. On the other hand, fish vessels have domestic buyers, commonly known as commission agents, and do not face many conditions to fulfill (most conditions are met by the commission agents) and hence cost less to maintain compared to shrimp vessels.

Vessel age is measured in years. All vessels in this study are imported second hand vessels and their starting age is the first entry of operation in the Bangladesh marine water. Data shows that shrimp vessel age varies between 4 and 25 years with an average of 18 years and the standard deviation is 5 years. On the other hand, fish vessels age varies between 2 and 19 years with an average of 11 years and the standard deviation is 5 years. Data used in this study shows that shrimp vessels are older than fish vessels.

Gear length is measured in meters and varies from 22 to 32 metres for shrimp vessels, with a standard deviation of 2 metres and average of 23 metres. On the other hand, gear length varies from 30 to 40 metres for fish vessels, with a standard deviation of 4 metres and average of 33 metres. The average length of gear for fish vessels is much higher than that of shrimp vessels.

A binary variable market orientation is used to capture whether the vessel is domestic market oriented (one) or foreign market oriented (zero). Most shrimp vessels export their harvest directly to the foreign market and only a few of them export via domestic commission agents. But, most fish vessels export their harvest via domestic commission agents and only a few of them export directly to the foreign market.

The binary variable for owner use in this study indicates whether the vessel is multiple owners managed (one) or single owner managed (zero). The number of owners varies between 1 and 10 for shrimp vessels with an average of 4 and standard deviation is 3. On the other hand, the number of owner varies between 1 and 10 for fish vessels with an average of 3 and standard deviation is 4. Data shows that the average number of owners in shrimp vessels is higher than that of fish vessels. Vessel specific dummy variables used in this study captures vessel-specific fixed effects and describes vessels-specific characteristics not captured by the inefficiency model.

The summary statistics of the variables used in this study for both shrimp and fish vessels are shown in Table 2.3 (Appendix A).

2.4 Econometric Specifications

Generalized likelihood ratio tests are used to confirm the functional form and specification for both shrimp and fish vessels, with the relevant test statistics given by:

$$LR = -2\{\ln[L(H_0)] - \ln[L(H_1)]\} \tag{2.10}$$

Where $L(H_0)$ and $L(H_1)$ are the values of the likelihood function under the null and alternative hypotheses. The correct critical values for the test statistics are drawn from both Kodde & Palm (1986) and from the normal χ^2 statistic. The Kodde & Palm (1986) tables are used for the test of the one sided inefficiency term and the normal χ^2 statistic is used for the other tests. To confirm the functional form and the specification, various hypotheses are tested.

2.4.1 Hypothesis test and model specification: shrimp vessel

The hypothesis tests for shrimp vessels are presented in Table 2.4 (Appendix A). At a 5 per cent level of significance, the generalized likelihood ratio tests for shrimp vessels in Table 3.4 show the inefficiency effects are stochastic and the stochastic production frontier is appropriate ($H_0 : \gamma = 0$ is rejected). The tests also show the Translog functional form of the production function is suitable ($H_0 : \beta_{nm} = \beta_{tt} = \beta_{nt} = 0$ is rejected and $n, m = 1,2,3$). The test confirms the presence of technical inefficiency ($H_0 : \gamma = \delta_0 = \delta_1 = ... = \delta_{23} = 0$ is rejected) and shows that the distribution of inefficiency effects is neither half-normal ($H_0 : \delta_0 = \delta_1 = ... = \delta_{23} = 0$ is rejected) nor, truncated normal ($H_0 : \delta_1 = ... = \delta_{23} = 0$ is rejected). The test also confirms that both vessels' specific fixed effects and gear length significantly affect the technical efficiency of the shrimp vessels ($H_0 : \delta_7 = ... = \delta_{23} = 0$ and $H_0 : \delta_4 = 0$ are rejected) and hence, are included in the technical inefficiency effect model. The generalized likelihood ratio tests also show an existence of technical change ($H_0 : \beta_t = \beta_{tt} = \beta_{nt} = 0$ is rejected and $n = 1,2,3$), which is non-neutral ($H_0 : \beta_{tt} = \beta_{nt} = 0$ is rejected and $n = 1,2,3$). Thus, the Translog production function and the technical inefficiency effect model for shrimp vessels are confirmed. Comparison of these different models for shrimp vessels are presented in Table 2.5 and 2.6 (Appendix A).

The specification of the Translog production function for shrimp vessels is:

$$\ln Y_{it} = \beta_0 + \sum_{n=1}^{3} \beta_n \ln X_{nit} + \beta_4 Year_i + \frac{1}{2} \sum_{n=1}^{3} \sum_{m=1}^{3} \beta_{nm} \ln X_{nit} . \ln X_{mit} + \beta_t t + \beta_{tt} t^2 + \sum_{n=1}^{3} \beta_{tn} \ln X_{nit} . t + v_{it} - u_{it} \tag{2.11}$$

Where, vessel i=1,2,3,……, 18 and year t= 1,2,…,7; Y_{it} is the value of total catch, X_{1it} is the engine power, X_{2it} is the size of crew, X_{3it} is the fishing days and t is time trend. $Year_i$ is a dummy variable for the year 2004.

Vessel specific factors are used in the technical inefficiency model for shrimp vessels:

$$\ln u_{it} = \delta_0 + \sum_{n=1}^{4} \delta_n \ln z_{nit} + \sum_{m=1}^{2} \delta_m D_{mi} + \sum_{k=1}^{17} \delta_k V_{ki} + w_{it} \tag{2.12}$$

Where, z_{1it} is the storage capacity, z_{2it} is the quality expenditure that captures the cost of hygiene and quality control, and laboratory certificate, z_{3it} is the vessels age and z_{4it} is the gear length. D_{1i} and D_{2i} are dummy variables for market orientation and ownership of the vessels, respectively. V_{ki} is a dummy variable that captures vessel specific fixed effects, those are not captured anywhere in the model and k=1,2,3,……, 17.

2.4.2 Hypothesis test and model specification: fish vessel

The hypothesis tests for fish vessels are presented in Table 2.7 (Appendix A). At a 5 per cent level of significance, the generalized likelihood ratio tests in Table 2.7 show the inefficiency effects are stochastic and the stochastic production frontier is appropriate ($H_0 : \gamma = 0$ is rejected). The tests also show the Translog functional form of the production function is suitable ($H_0 : \beta_{nm} = \beta_{tt} = \beta_{nt} = 0$ is rejected and $n, m = 1,2,3$). The test confirms the presence of technical inefficiency ($H_0 : \gamma = \delta_0 = \delta_1 = ... = \delta_4 = 0$ is rejected) and shows that the distribution of inefficiency effects is neither half-normal ($H_0 : \delta_0 = \delta_1 = ... = \delta_4 = 0$ is rejected) nor, truncated normal ($H_0 : \delta_1 = ... = \delta_4 = 0$ is rejected). The test also confirms that both storage capacity and a vessels' specific fixed effects are not significant for the technical efficiency of fish vessels ($H_0 : \delta_{storage\_capacity} = 0$ and $H_0 : \delta_5 = ... = \delta_{11} = 0$ are accepted) and hence, are excluded from the technical inefficiency effect model, but, the gear length significantly affects the technical efficiency of the fish vessels ($H_0 : \delta_2 = 0$ are rejected) and, hence is included in the technical inefficiency effect model. The generalized likelihood ratio tests also show an existence of technical change ($H_0 : \beta_t = \beta_{tt} = \beta_{nt} = 0$ is rejected and $n = 1,2,3$), which is non-neutral ($H_0: \beta_{tt} = \beta_{nt} = 0$ is rejected and $n = 1,2,3$). Thus, the Translog production function and the technical inefficiency effect model for fish vessels are confirmed. Comparison of these different models for fish vessels are presented in Table 2.8 and 2.9 (Appendix A).

The specification of the Translog production function for fish vessels is:

$$\ln Y_{it} = \beta_0 + \sum_{n=1}^{3} \beta_n \ln X_{nit} + \beta_4 Year_i + \frac{1}{2}\sum_{n=1}^{3}\sum_{m=1}^{3} \beta_{nm} \ln X_{nit} . \ln X_{mit} + \beta_t t + \beta_{tt} t^2 + \sum_{n=1}^{3} \beta_{tn} \ln X_{nit} . t + v_{it} - u_{it} \tag{2.13}$$

Where, vessel i=1,2,3,……, 8 and year t= 1,2,…,7; Y_{it} is the value of total catch, X_{1it} is the engine power, X_{2it} is the size of crew, X_{3it} is the fishing days and t is time trend. $Year_i$ is a dummy variable for the year 2004.

Vessel specific factors are used in the technical inefficiency model for fish vessels:

$$\ln u_{it} = \delta_0 + \sum_{n=1}^{2} \delta_n \ln z_{nit} + \sum_{m=1}^{2} \delta_m D_{mi} + w_{it} \tag{2.14}$$

Where, z_{1it} is the vessels age and z_{2it} is the gear length. D_{1i} and D_{2i} are dummy variables for market orientation and ownership of the vessels, respectively.

2.5 Results

Maximum Likelihood Estimates (MLE) is obtained using Frontier 4.1 (Coelli 1996) for both shrimp and fish vessels. The Frontier 4.1 program follows a three-step procedure. In the first step, Ordinary Least Squares (OLS) estimates of the parameter of the production function are obtained, which provides unbiased estimators of all parameters except the intercept. The second step conducts a two-phase grid search of gamma and OLS estimates are used as starting values. The intercept and variance parameters are adjusted by the Corrected Ordinary Least Squares (COLS). In the third step, Davidson-Fletcher-Powell Quasi-Newton method is used to obtain the final MLE. The values selected in the grid search are used as starting values in this iterative procedure. The estimates of the parameters of both the Translog model and the inefficiency effects model of this study are presented in Table 2.10 and 2.11 for both shrimp and fish vessels, respectively (Appendix A).

2.5.1 Theoretical consistency of production function

The theoretical consistencies of both production functions for shrimp and fish vessels are checked and results are reported in Table 2.12. Translog function consists of quadratic terms, which shows a parabolic form that implies increasing and decreasing branches by definition causing inconsistencies in monotonicity and/or violation in curvature conditions (Sauer et al 2006).

Table 2.12 **Theoretical consistency**

		Shrimp vessel		Fish vessel	
Monotonicity	f_1	0.16	> 0	0.44	> 0
	f_2	0.53	> 0	0.45	> 0
	f_3	0.39	> 0	0.61	> 0
Law of diminishing returns	f_{11}	-0.48	< 0	-2.15	< 0
	f_{22}	-1.05	< 0	-0.37	< 0
	f_{33}	-0.28	< 0	-0.33	< 0
	f_{12}	0.71	> 0	3.39	> 0
	f_{13}	0.38	> 0	0.40	> 0
	f_{23}	0.52	> 0	0.42	> 0
Curvature (quasi-concavity)*	$\lvert\overline{B_1}\rvert$	-0.03	< 0	-0.19	< 0
	$\lvert\overline{B_2}\rvert$	0.28	> 0	1.85	> 0
	$\lvert\overline{B_3}\rvert$	-0.37	< 0	1.27	> 0

Note: * denotes B is Boarded Hessian
Source: Author's calculation

In this study, both production functions show that output increases monotonically with all inputs for both shrimp and fish vessels; and the law of diminishing returns holds for both production functions. A slight violation of curvature condition for fish vessels is reported and curvature condition for shrimp vessels is fulfilled. For shrimp vessels, all three principle leading minors of the Bordered Hessian matrix alternate its sign, but for fish vessels, though the first two principle minors alternate its sign, the last one doesn't.

So, it is confirmed that the production function of shrimp vessels is strictly quasi-concave and the level set is convex as the input bundle is negative definite, but the curvature condition for fish vessels is violated. Literature shows that violation of curvature condition for translog production function can be expected and this is caused by logarithmic transformation of input variables (Sauer et al 2006). Overall, production function for shrimp vessels is theoretically consistent, while the production function for fish vessels shows consistency in monotonicity, but, inconsistence with the curvature condition.

However, monotonicity condition is particularly important for estimating relative efficiency of individual firms for a reasonable interpretation of the results (Hennigsen & Henning 2009). As monotonicity conditions for both production functions are consistent, the estimated production functions for both shrimp and fish vessels are accepted as well-behaved production functions. Monotonicity of translog production function requires all marginal products with respect to all inputs should be positive and thus elasticity of outputs with respect to all inputs is non-negative. Marginal products of all inputs are calculated using mean values of output, input variables and output elasticities of inputs.

2.5.2 Output elasticity of inputs and elasticity of scale

The estimated results of both production functions show output elasticity for all inputs are positive and hence, the marginal products of all inputs are positive (Table 2.12). The positive value of output elasticity for all inputs suggests that the estimated translog production function is a well-behaved production technology (Sharma & Leung 1999; Greenville et al 2006). The output elasticity with respect to all inputs and the elasticity of scale for both shrimp and fish vessels are reported in Table 2.13.

Table 2.13 **Output elasticity with respect to inputs**

Year	Engine power		Crew		Fishing days		Elasticity of scale	
	Shrimp vessel	Fish vessel	Shrimp vessel	Fish vessel	Shrimp vessel	Fish vessel	Shrimp vessel	Fish vessel
2001	0.07	0.22	0.89	0.05	1.30	1.28	2.26	1.54
2002	0.11	0.24	0.82	0.17	1.15	1.07	2.08	1.47
2003	0.15	0.27	0.75	0.28	0.99	0.85	1.90	1.40
2004	0.22	0.28	0.66	0.39	0.79	0.65	1.68	1.32
2005	0.20	0.33	0.65	0.53	0.75	0.42	1.60	1.27
2006	0.24	0.35	0.58	0.64	0.60	0.20	1.43	1.20
2007	0.33	0.36	0.48	0.74	0.37	0.01	1.18	1.11
Mean	0.19	0.29	0.69	0.40	0.85	0.64	1.73	1.33

Source: Author's calculation

Table 2.13 shows that during 2001-07 mean output elasticity with respect to engine power, size of crew and fishing days for shrimp vessels are 0.19, 0.69 and 0.85, respectively and for fish vessels are 0.29, 0.40 and 0.64 respectively.

Results show that for both shrimp and fish vessels, the mean output elasticity associated with fishing days is higher, followed by size of crew and engine power. The elasticity associated with fishing days for shrimp vessels (0.85) is higher than fish vessels (0.64). A larger elasticity of days at sea (1.25) is estimated by Sharma & Leung (1999) for mid-Atlantic scallop fishery based on the estimated results of Kirkley et al (1995); and elasticity of days fished (1.233) is estimated by Greenville et al (2006) for NSW ocean prawn trawl fishery. The elasticity of trip days (0.71) estimated by Sharma & Leung (1999) for longline fishery in Hawaii is also quite large. It is noted that the elasticity associated with fishing days for both shrimp and fish vessels is decreasing over time.

The elasticity of output associated with size of crew is also higher for shrimp vessels (0.69) compare to fish vessels (0.40). Sharma & Leung (1999) estimated the highest elasticity (0.84) in crew size for longline fishery in Hawaii and the study also calculated the elasticity of crew size (0.48) for mid-Atlantic scallop fishery based on the estimated results of Kirkley et al (1995). Output elasticity associated with size of crew also shows a similar trend as fishing days for shrimp vessels, which is, decreasing over time and an opposite trend for fish vessels, that is, increasing over time.

Results show that elasticity associated with engine power for shrimp vessels (0.19) is smaller than that of fish vessels (0.29). Elasticity of output associated with engine power of fish vessels (0.29) is almost similar to the elasticity of output associated with the engine power (0.25), estimated for Australia's banana prawn fishery (Kompas et al 2004). The output elasticity associated with engine power for both shrimp and fish vessels shows an increasing trend over time and is smaller compared to fishing days and size of crew for both vessels.

During 2001-2007, the mean elasticity of scale for shrimp and fish vessels is 1.73 and 1.33, respectively. Results show that both shrimp and fish vessels are operating at Increasing Returns to Scale (IRS) with a decreasing trend. Studies on Australia's south east trawl fishery (Kompas & Che 2005) and Australia's banana prawn fishery (Kompas et al 2004) show Constant Returns to Scale (CRS); Swedish trawl fishery (Eggert 2001) and Solomon Island pole and line fishery (Campbell & Hand 1998) show Decreasing Returns to Scale (DRS); while NSW Australia ocean prawn trawl fishery (Greenville et al 2006), longline fishery in Hawaii (Sharma & Leung 1999) and mid-Atlantic sea scallop fishery (Kirkley et al 1995) show IRS. The IRS of these fisheries are calculated as 2.628, 1.87 and above 2, respectively. The returns to scale is not reported in the study done by Kirkley et al (1995), but estimated by Sharma & Leung (1999) based on Kirkley et al (1995)'s results.

Between 2001 and 2007, the estimated change in scale of shrimp vessels varies from -0.02 to 0.06 with a mean of 0.01 and fish vessels varies from -0.04 to 1.38 with a mean of 0.19, which indicates the mean change in the scale of fish vessels is much higher than that of shrimp vessels.

IRS indicates two possible implications in the scale of operation of vessels. The first implication is the existence of small vessels in both shrimp and fish vessels, which are too small in its scale of operation. The second implication is the use inputs, which shows that vessels' are using high proportion of inputs and this leads to an increase in output that is proportionately more than the use of inputs. Thus the elasticity of scale for both shrimp and fish vessels suggests that the scale efficiency of both shrimp and fish vessels can be improved by removing small vessels so that the remaining vessels can adjust the use of inputs in its production process.

2.5.3 Technical efficiency

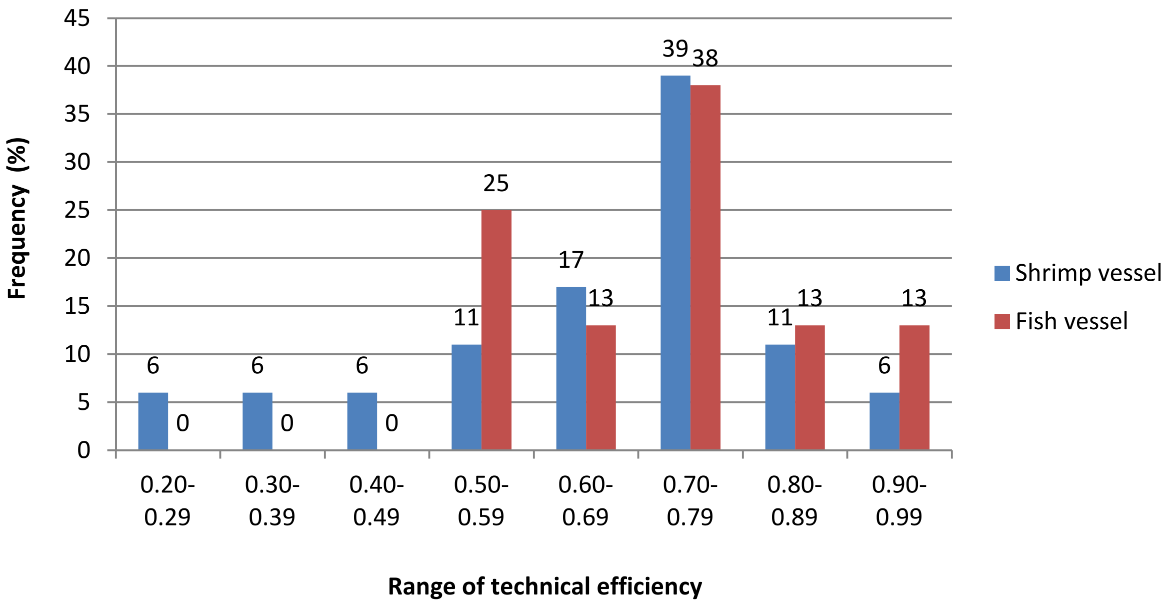
The value of gamma for both shrimp and fish vessels is 0.99 and highly significant, which is similar to Kirkley et al (1995) and Kompas & Che (2005). Gamma shows that the deviation in output for both shrimp and fish vessels is due to inefficiency effects (u_{it}), although the random effect (v_{it}) still matters.

The predicted mean efficiency score between 2001 and 2007 of shrimp vessels vary from 0.25 to 0.94 with a mean technical efficiency of 0.65 and fish vessels vary from 0.51 to 0.91 with a mean technical efficiency of 0.71. The mean technical efficiency for both shrimp vessels (0.65) and fish vessels (0.71) indicate that although vessels are operating close to efficient frontier, inefficiency exists for both shrimp (35%) and fish (29%) vessels, that is, vessels are not producing a maximum level of output with the given set of inputs. It can be seen from the mean actual output and frontier output for both shrimp and fish vessels depicted in Figure 2.3 (Appendix B), which shows that with the given set of inputs, vessels are producing below (actual output) the maximum (frontier output) level of output.

Studies on Australian south east trawl fishery (Kompas & Che 2005), longline fishery in Hawaii (Sharma & Leung 1999), mid-Atlantic sea scallop fishery (Kirkley et al 1995), Australia's banana prawn fishery (Kompas et al 2004) and Swedish trawl fishery (Eggert 2001) also show existence of inefficiency in these fisheries and the estimated mean technical efficiency of theses fisheries are 0.92 0.84, 0.75, 0.774 and 0.658, respectively.

The frequency distribution of estimated technical efficiency for both shrimp and fish vessels are shown in Figure 2.4. The frequency distribution of this study shows most (39%) shrimp vessels' technical efficiency is in the range of 0.70-0.79 followed by the range of 0.60-0.69 (17%), 0.80-0.89 (11%) and 0.50-0.59 (11%). The lowest range of technical efficiency scores of shrimp vessels is 0.20-0.29 and 6 percent of shrimp vessels' technical efficiency lies in this range. Result also show that most (38%) fish vessels' technical efficiency lies in the similar range (0.70-0.79) of shrimp vessels, followed by 0.50-0.59 (25%), which is the lowest range of technical efficiency score of fish vessels.

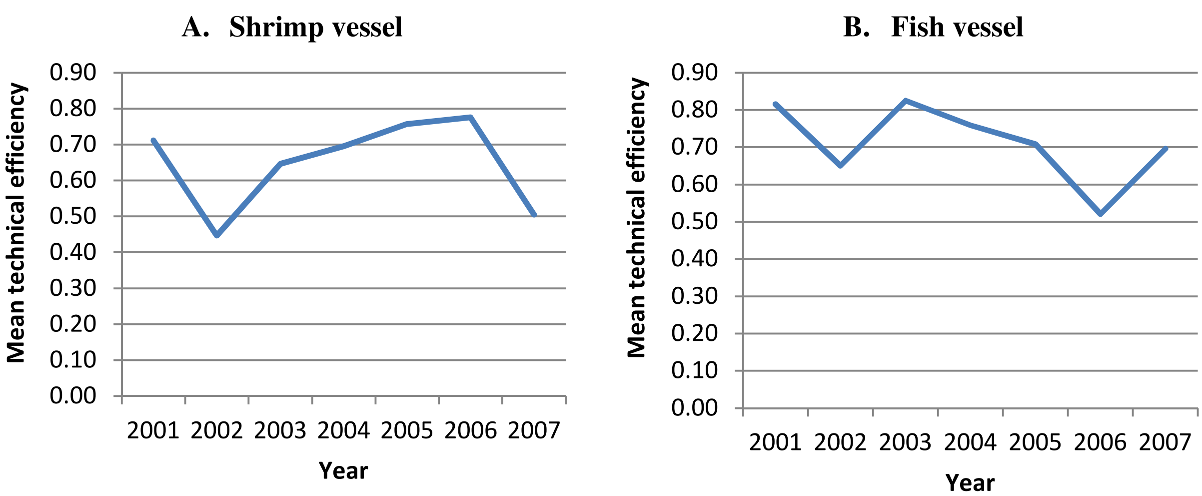
Figure 2.4 **Frequency distribution of technical efficiency**



Source: Author's calculation

The mean efficiency of shrimp and fish vessels over time in Figure 2.5 shows that between 2001 and 2003, the technical efficiency of both shrimp and fish vessels have similar trends (first declining and then increasing), but, different trends between 2004 and 2007. Between 2004 and 2006, the technical efficiency of shrimp vessels shows an increasing trend, while fish vessels show a decreasing trend. On the other hand, between 2006 and 2007 a declining trend in shrimp vessels and an increasing trend in fish vessels are seen. These trends may be due to policy changes in 2000 and 2004.

Figure 2.5 **Technical Efficiency (TE) over time**



Source: Author's calculation

The main sources of technical inefficiency are identified in this study from the estimated technical inefficiency effect model. All variables included in the technical inefficiency effect model for both shrimp and fish vessels are statistically significant (Table 2.10 and 2.11, Appendix A). The estimated technical inefficiency effect model shows that use of older vessels is a common source of technical inefficiency for both shrimp and fish vessels as vessel age variable for both shrimp and fish vessels has positive sign. This indicates that both vessels aren't producing at the maximum level and the existence of old vessels show that input controls may make replacement of vessels more difficult. Results also show that the overuse of inputs is also an important source of technical inefficiency for both shrimp and fish vessels. For example, larger shrimp vessels are technically inefficient as storage capacity variable has positive sign and fish vessels those using larger gears are technically inefficient as gear length variable has positive sign. That is, using these inputs, shrimp and fish vessels aren't producing at the maximum levels of output. This also indicates that input controls induce vessels' operators to use more unregulated inputs intensively.

Results show that vessels those are overusing inputs are mainly domestic market oriented vessels as market orientation variable for both shrimp and fish vessels have positive sign. The estimated results show shrimp vessels with high quality control costs and shrimp vessels using small gear are technically efficient, as all these variables have a negative sign in the estimated model. Results also show that both shrimp and fish vessels with single ownership are technically efficient. A generalized likelihood ratio test shows that vessel specific fixed effect also affects the technical efficiency of shrimp vessels.

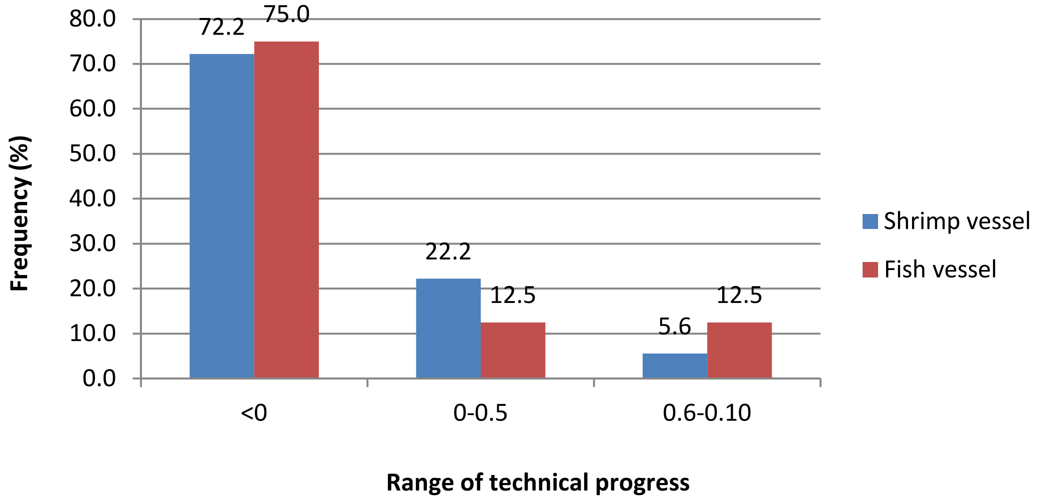
2.5.4 Technical progress

Non-neutral[41] technical change exists in both shrimp and fish vessels, which is confirmed by the generalized ratio test. The estimated mean technical progress of both shrimp and fish vessels is the same and the rate of mean technical progress for both vessels is -0.06. The rate of technical progress varies between 2001 and 2007 for both

[41] Technical change is neutral when it raises the productivity of all factors inputs in production (e.g., capital and labor) by the same proportion. It is non-neutral when it raises the productivity of some factors more than others.

vessels and the rate varies from -0.17 to 0.08 for shrimp vessels and from -0.15 to 0.07 for fish vessels. The estimated results show that only 25 percent fish vessels and 27.8 percent shrimp vessels have positive technical progress (Figure 2.6) and most shrimp (72.2 percent) and fish (75 percent) vessels' technical progress is negative.

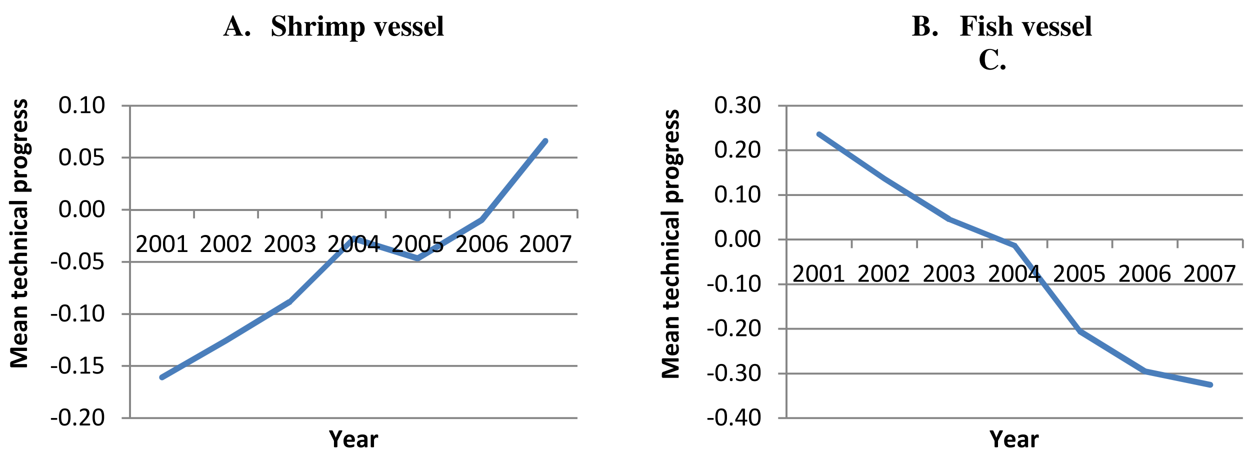
Figure 2.6 **Frequency distribution of technical progress**



Source: Author's calculation

The mean technical progress of shrimp and fish vessels over time in Figure 2.7 shows the mean technical progress of shrimp vessels is increasing and the mean technical progress of fish vessels is decreasing over time.

Figure 2.7 **Technical Progress (TP) over time**



Source: Author's calculation

The estimated results in Table 2.10 and 2.11 (Appendix A) show that both the coefficients of time squared (0.02 for shrimp vessels and -0.05 for fish vessels) are highly significant, indicating that the rate of technical change of shrimp vessels is increasing at an increasing rate through time, while the rate of technical change of fish vessels is decreasing at a decreasing rate. The coefficient of time interacted with engine power, crew and fishing days are positive, negative and negative respectively for shrimp vessels; and positive, positive and negative respectively for fish vessels. The results suggest that over this period, for shrimp vessels, technical change is capital-saving but both effort-using and labour-using; and for fish vessels, technical change is both capital-saving and labour-saving, but effort-using.

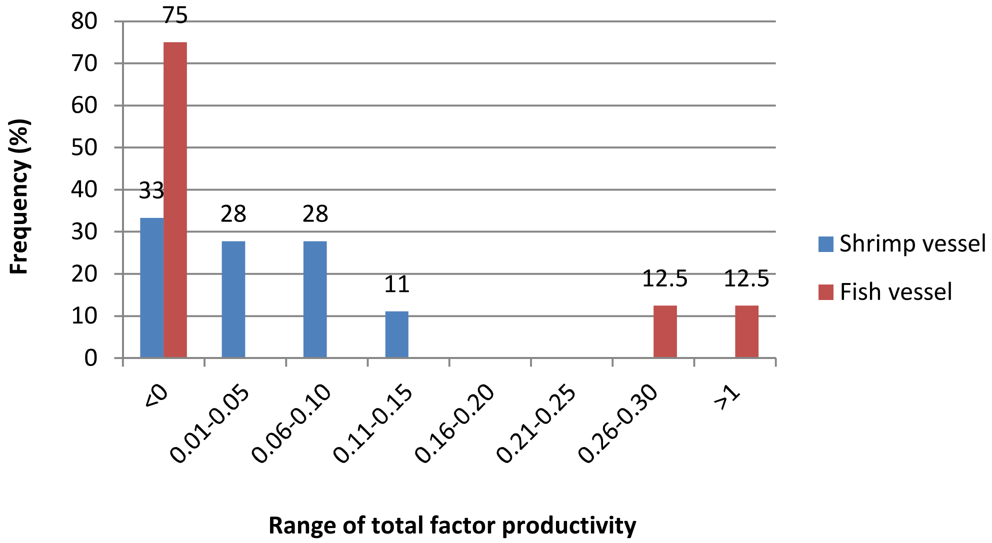
The results indicate that for shrimp vessels, the isoquant is shifting inwards at a faster rate over time in the capital intensive part of the input-space, which indicates that high depreciation costs of engines that are too old. On the other hand, for fish vessels, the isoquant is shifting inwards at a faster rate over time in both capital and labour intensive parts of the input-space, which indicates that high depreciation costs of engines that are too old and high marginal cost of production. The effort-using results for both shrimp and fish vessels indicate that too much effort is being used over this period and the negative sign of the coefficient indicating that both shrimp and fish vessels are producing low output with high effort. It also shows an indication of decline in high-valued stock as shrimp vessels are more concentrated in high-valued catch and an indication of need for improvement of fishing technology as a declining trend of technical change of fish vessels is seen in Figure 2.7.

2.5.5 Productivity

The marginal product of engine power, crew and fishing days for shrimp vessels are 0.16, 0.53 and 0.39, respectively and for fish vessels are 0.44, 0.45 and 0.61, respectively (Table 2.12). Variations in marginal productivity of inputs show that the changes in output in shrimp vessels is mainly due to an additional use of crew followed by an additional increase in fishing days and an additional use of engine power. On the other hand, changes in output in fish vessels is mainly due to an additional increase in fishing days followed by an additional use of both number of crew and engine power.

The mean total factor productivity (TFP) of shrimp and fish vessels is -0.08 and 0.11, respectively. Between 2001 and 2007, the total factor productivity of shrimp vessels varies from -0.19 to -0.01 and fish vessels varies from -0.20 to 1.45. The frequency distribution of TFP in Figure 2.8 show that most fish vessels' (75 percent) TFP is negative and only 25% vessel's TFP is positive, but, quite large. As a result, the mean TFP of fish vessels is positive. On the other hand, only 33 percent shrimp vessels' TFP is negative and 67 percent vessels' TFP is positive, but, quite small. As a result, the mean TFP of shrimp vessels are negative.

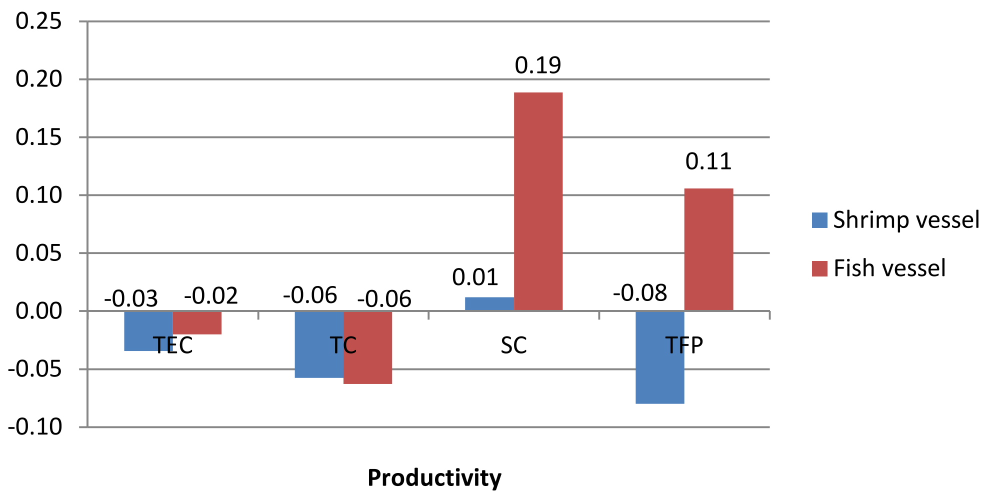
Figure 2.8 **Frequency distribution of total factor productivity**



Source: Author's calculation

The mean total factor productivity of shrimp and fish vessels in Figure 2.9 shows that the negative TFP of shrimp vessels are mainly due to both technical efficiency change and technical change, while the positive TFP of fish vessels are mainly due to scale change.

Figure 2.9 **Mean Total Factor Productivity (TFP)**



Source: Author's calculation

The mean technical efficiency change (TEC), technical change (TC), scale change (SC) and total factor productivity (TFP) of both shrimp and fish vessels over time is shown in Figure 2.10 (Appendix B). The trend of TFP of both shrimp and fish vessels in Figure 2.10 show that the sources of TFP vary in different periods during 2002-2007, which is summarize in Table 2.14.

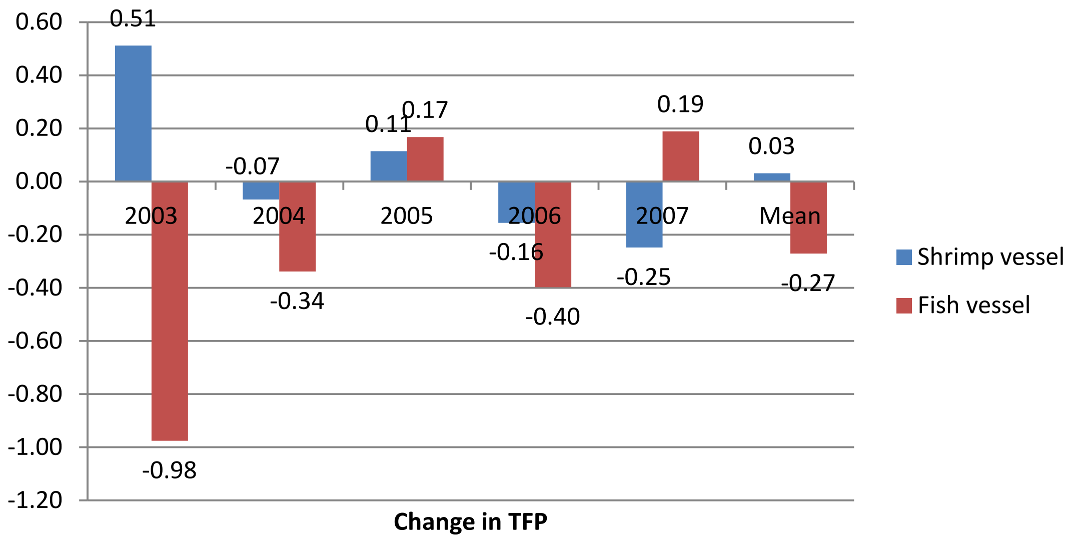
Table 2.14 **Sources of TFP over time**

Period	Sources of TFP	
	Shrimp vessel	Fish vessel
2002-03	TEC	SC
2003-04	TEC	TC and TEC
2004-05	TEC, TC and SC	SC
2005-06	TEC, TC and SC	TEC, TC and SC
2006-07	TEC and SC	TEC

Source: Figure 2.10

Overall, the change in TFP during 2003-07 is positive for shrimp vessels (0.03) and negative for fish vessels (-0.27). The change in TFP over time for both vessels is shown in Figure 2.11.

Figure 2.11 **Change in TFP over time**



Source: Author's calculation

2.6 Conclusion

This study is the first kind of study to investigate the performance of industrial vessels of Bangladesh, where industrial vessels are divided into two fleets: shrimp and fish and both are managed by input control. The performance of vessels in this study is measured in terms of efficiency and productivity. Efficiency is measured using Translog production function and technical efficiency effect model; and productivity is measured using Total Factor Productivity.

Considering heterogeneity between shrimp and fish fleets, separate models are estimated for both. Stochastic Frontier Analysis is used to measure change in technical efficiency, technical change, scale change and total factor productivity. A normalized and balanced panel data set for both shrimp and fish vessels for the period 2001-2007 are used. Theoretical consistencies of translog production function for both vessels are checked. Output elasticity associated with all inputs, elasticity of scale and marginal productivity of all inputs for both vessels are also examined. Results show that the deviation in output for both shrimp and fish vessels are mainly due to inefficiency effects, although the random effect is still relevant. Both production functions show that output increases monotonically with engine power, size of crew and fishing days. The positive value of output elasticity associated with all inputs for both vessels shows a well-behaved production technology and the production technology exhibits increasing returns to scale for both vessels.

Results show that during 2001-2007, the mean TFP of shrimp vessels is negative and fish vessels are positive and the negative TFP of shrimp vessels is mainly due to both technical efficiency change and technical change, while the positive TFP of fish vessels is mainly due to scale change. Results show that technical efficiency change, technical change and scale change are important sources of total factor productivity of Bangladesh industrial marine fishery. During 2001-2007, though the mean technical efficiency of fish vessels is higher than shrimp vessels, both vessels are producing below the maximum level of output. Results show that all vessels of both fleets engaged in fishing over this period are too old to be technically efficient. The overuse of unregulated inputs is also an important source of technical inefficiency of both fleets. Results also show that mainly domestic market oriented vessels in both fleets are overusing inputs. The estimated results show that adequate quality control, use of small gear and single ownership are important for vessels to be technically efficient. Results indicate that input controls may make replacement of vessels more difficult and hence vessels' operators are intensively using more unregulated inputs.

Traditionally, shrimp vessels exploit high-valued stocks and fish vessels exploit low-valued stocks. All vessels in both shrimp and fish fleets of industrial marine fishery are export-oriented and export their catch either directly to the foreign market or via commission agent from the domestic market. The number of foreign buyers of estimated shrimp vessels is higher, while the number of domestic buyers is higher for fish vessels. In this study, a common price of catch considered for all vessels, which varies over time and the value of output for fish vessels are higher due to high volumes of catch. High volumes of catch of fish vessels may be due to two reasons. First of all, a sharp increase in volume of total fish vessels, while volume of total shrimp vessels is almost constant over time. Second, most fish vessels incur minimal costs for maintaining their vessels given that these costs are largely met by commission agents, whereas shrimp vessel operators incur greater costs to maintain quality control of their vessels in order to meet the conditions of foreign buyers. As a result, fish vessels are exploiting more stocks compared to shrimp vessels, but not producing maximum with the given sets of inputs used in fishing.

The estimated non-neutral technical progress of both fleets is negative, technical change over time of this study shows that, the technical change of shrimp vessels are increasing and fish vessels are decreasing over time. Results show that over the period, the technical change of shrimp vessels is capital-saving but both effort-using and labour-using; and the technical change of fish vessels is both capital-saving and labour-saving, but effort-using. Results indicate that vessels in both fleets are using too much effort over the period, but producing low output. This may be due to different reasons for shrimp and fish vessels. As the number of vessels in shrimp fleet is almost constant over time and an increasing trend in technical change is also seen for vessels in shrimp fleet, vessels in shrimp fleet is producing low output may be a result of a decline in high-valued species (though the stock information is not known). On the other hand, as the number of vessels in fish fleet is shraply increasing over time and a decreasing trend in technical change is seen in fish fleet, vessels in fish fleet is producing low output may be a result of a use of inadequate fishing technology.

The study indicates that both shrimp and fish fleets in industrial marine fisheries of Bangladesh are producing below the maximum level of output and are too small in their scale of operation. Second, input control induces vessels operators to intensify usage of unregulated inputs. Third, vessels in both fleets are too old to be technically efficient.

The inward shift of production of all vessels in both fleets towards capital-intensive part of input space shows a high depreciation costs and low return. Fourth, marginal cost of production varies across fleets. Shrimp fleets face low marginal costs of production in employing labour; while fish fleet's marginal cost of production is high. The inward shift of production of fish vessels towards labour-intensive part of input space shows a high marginal cost of production and the outward shift of shrimp vessels towards labour-intensive part of input space shows a low marginal cost of production. Fifth, decline in catches in both fleets are confirmed from the study. The outward shift of production of all vessels in both fleet shows over the period too much effort is being used and indicates a possible decline in catch. The high-valued catch in industrial marine fisheries of Bangladesh is in decline may be due to decline in stock as increasing trend in fishing technology is reported from the technical change. The low-valued catch may be in decline due to an inadequate use of fishing technology as reported from the technical progress. Finally, the negative change in both technical efficiency and technical progress are adversely affecting the total factor productivity of all vessels in both fleets. Overall, the results of this study indicate that to improve vessels efficiency and productivity; to increase the level of high-valued stocks and to introduce adeaquate fishing technology for low-valued stocks an alternative management strategy for industrial marine fisheries of Bangladesh is needed.

Appendix A: Table

Table 2.3 **Summary statistics for key variables**

Variable	Unit	Average	Maximum	Minimum	Standard Deviation
A. Shrimp vessel*					
Total value	000, US$	943	2125	110	511
Engine power	Brake Horse Power (BHP)	664	960	450	168
Total crew	Number	32	41	26	6
Fishing days	Days per year	175	246	14	43
Storage capacity	Tonnes	76	181	41	33
Quality control	000, US$	6	16	0.2	4
Vessel age	Year	18	25	4	5
Gear	Metre	23	32	22	2
Owner	Number	4	10	1	3
B. Fish vessel**					
Total value	000, US$	1391	2459	435	511
Engine power	Brake Horse Power (BHP)	694	960	450	205
Total crew	Number	30	41	24	6
Fishing days	Days per year	169	254	120	28
Storage capacity	Tonnes	90	119	54	24
Quality control	000, US$	0.17	0.19	0.15	0.01
Vessel age	Year	11	19	2	5
Gear	Metre	33	40	30	4
Owner	Number	3	10	1	3

Note: * denotes balanced panel data: 126 observations for 18 shrimp vessels, 2001-07
** denotes balanced panel data: 56 observations for 8 fish vessels, 2001-07
Source: Marine Fisheries Department 2009, 'Unpublished office records', Chittagong.

Table 2.4 **Hypothesis test for model specification: shrimp vessel**

Hypothesis	LR test	Critical value	Decision
1. $H_0 : \gamma = \delta_0 = \delta_1 = ... = \delta_{23} = 0$ (No technical inefficiency)	123.55	$\chi^2_{.0(25)} = 37.652$	H_0 Rejected
2. $H_0 : \gamma = 0$ (Inefficiency effects are not stochastic)	123.55	$\chi^2_{.05(1)} = 2.706$	H_0 Rejected
3. $H_0 : \delta_0 = \delta_1 = ... = \delta_{23} = 0$ (Inefficiency effects have a half-normal distribution)	109.20	$\chi^2_{.0(24)} = 36.415$	H_0 Rejected
4. $H_0 : \delta_1 = ... = \delta_{23} = 0$ (Inefficiency effects have a truncated-normal distribution)	106.96	$\chi^2_{.0(23)} = 35.172$	H_0 Rejected
5. $H_0 : \delta_7 = ... = \delta_{23} = 0$ (Inefficiency effects do not come from vessels specific fixed effects)	88.78	$\chi^2_{.0(17)} = 27.587$	H_0 Rejected
6. $H_0 : \beta_t = \beta_{tt} = \beta_{nt} = 0$ (No technical change)	47.16	$\chi^2_{.05(5)} = 11.070$	H_0 Rejected
7. $H_0 : \beta_{tt} = \beta_{nt} = 0$ (Hick-neutral technical change)	39.92	$\chi^2_{.05(4)} = 9.488$	H_0 Rejected
8. $H_0 : \beta_{nm} = \beta_{tt} = \beta_{nt} = 0$ (Cobb Douglas production function)	154.60	$\chi^2_{.05(10)} = 18.307$	H_0 Rejected
9. $H_0 : \delta_4 = 0$ (Inefficiency effects do not come from gear length)	21.1	$\chi^2_{.05(1)} = 3.841$	H_0 Rejected

Source: Author's calculation

Table 2.5 **Model comparison-1: shrimp vessel**

	Model-1*		Model- 2		Model-3		Model-4	
	coefficient	t-ratio	coefficient	t-ratio	coefficient	t-ratio	coefficient	t-ratio
Production Function								
$Constant$	0.73	4.88	-0.04	-0.18	-0.13	-0.62	0.03	0.17
$\ln X_1$	-0.25	-2.36	0.12	0.62	0.12	0.62	-0.23	-1.07
$\ln X_2$	1.20	99.12	0.63	3.95	0.64	4.09	1.01	6.42
$\ln X_3$	1.52	8.47	0.99	3.06	1.05	3.48	0.99	3.03
$Year\_2004$	0.05	1.74	0.20	2.32	0.20	2.34	0.28	5.38
t	-0.28	-7.81	-0.06	-0.84	-0.06	-0.90	-0.11	-2.45
$\ln X_1 * \ln X_1$	0.06	5.64	-0.11	-1.33	-0.10	-1.19	-0.20	-2.75
$\ln X_1 * \ln X_2$	-0.22	-11.40	0.07	1.33	0.07	1.33	0.04	0.76
$\ln X_1 * \ln X_3$	-0.16	-2.53	0.90	4.62	0.75	4.15	1.00	4.88
$\ln X_2 * \ln X_2$	0.36	10.89	0.21	4.48	0.21	4.56	0.33	8.81
$\ln X_2 * \ln X_3$	0.12	1.56	-0.52	-2.76	-0.34	-1.94	-0.47	-2.17
$\ln X_3 * \ln X_3$	0.30	13.43	0.21	1.80	0.21	1.98	0.10	0.81
t^2	0.02	27.48	0.01	0.91	0.01	1.08	0.01	2.08
$\ln X_1 * t$	0.04	5.44	0.03	1.78	0.03	1.54	0.02	1.13
$\ln X_2 * t$	-0.06	-5.83	-0.04	-2.68	-0.03	-2.27	-0.05	-3.72
$\ln X_3 * t$	-0.14	-8.41	0.20	3.94	0.20	4.94	0.23	4.87
Technical Efficiency Model								
$Constant$	-2.45	-3.82			-19.34	-0.70	-0.97	-1.46
$\ln Z_1$	1.97	6.39					-0.21	-1.44
$\ln Z_2$	-1.51	-118.02					-0.04	-0.36
$\ln Z_3$	0.08	1.22					-0.35	-1.46
$\ln Z_4$	-3.05	-15.60					-0.25	-0.70
D_market	0.55	1.02					-0.42	-0.86
$D\_ownership$	-1.37	-3.48					0.41	1.64
sigma-squared	0.15	15.14	0.27	5.13	5.57	0.75	0.25	3.92
gamma	0.99	1.E+03	0.93	2.E+01	0.99	1.E+02	0.99	3.E+07
LLF	22.70		-31.90		-30.78		-21.69	
LR test	123.55		14.35		16.59		34.77	
Mean Efficiency	0.65		0.70		0.78		0.64	

Note: * denotes vessel dummies in the technical efficiency model are not reported. $X_1 = engine\ power$, $X_2 = crew$, $X_3 = fishing\ days$, $Z_1 = storage\ capacity$, $Z_2 = quality\ control$, $Z_3 = vessel\ age$, $Z_4 = gear\ length$.

Source: Author's calculation

Table 2.6 **Model comparison-2: shrimp vessel**

	Model-1*		Model- 5*		Model-6*		Model-7*	
	coefficient	t-ratio	coefficient	t-ratio	coefficient	t-ratio	coefficient	t-ratio
Production Function								
$Constant$	0.73	4.88	0.18	1.47	0.22	1.61	0.55	1.52
$\ln X_1$	-0.25	-2.36	1.11	3.52	0.88	3.86	-0.92	-2.36
$\ln X_2$	1.20	99.12	0.26	1.47	0.53	1.51	2.08	2.82
$\ln X_3$	1.52	8.47	1.12	5.77	0.99	4.63	1.66	2.32
$Year\_2004$	0.05	1.74	-0.05	-0.68	-0.03	-2.84	0.05	0.41
t	-0.28	-7.81			-0.03	-2.30	-0.25	-4.15
$\ln X_1 * \ln X_1$	0.06	5.64	0.47	3.33	0.41	4.42	-0.27	-2.56
$\ln X_1 * \ln X_2$	-0.22	-11.40	-0.26	-3.07	-0.26	-2.27	0.04	0.41
$\ln X_1 * \ln X_3$	-0.16	-2.53	0.36	1.42	0.12	0.59	0.12	0.73
$\ln X_2 * \ln X_2$	0.36	10.89	0.18	3.69	0.24	2.80	0.59	3.02
$\ln X_2 * \ln X_3$	0.12	1.56	-0.07	-0.43	0.20	1.26	0.30	3.02
$\ln X_3 * \ln X_3$	0.30	13.43	0.15	1.46	0.07	0.62	0.00	-0.03
t^2	0.02	27.48					0.02	3.52
$\ln X_1 * t$	0.04	5.44					0.02	1.66
$\ln X_2 * t$	-0.06	-5.83					-0.05	-2.35
$\ln X_3 * t$	-0.14	-8.41					-0.08	-0.68
Technical Efficiency Model								
$Constant$	-2.45	-3.82	-1.12	-1.67	-1.08	-1.55	-0.14	-0.22
$\ln Z_1$	1.97	6.39	0.68	2.36	0.81	2.86	0.79	1.05
$\ln Z_2$	-1.51	-118.02	-1.00	-5.41	-0.97	-5.75	-0.79	-1.66
$\ln Z_3$	0.08	1.22	0.84	1.92	0.50	0.96	-0.29	-0.51
$\ln Z_4$	-3.05	-15.60	-1.47	-4.02	-1.41	-3.20		
D_market	0.55	1.02	0.81	1.24	0.41	0.63	-0.68	-1.09
$D\_ownership$	-1.37	-3.48	-0.98	-2.14	-0.78	-1.68	-0.74	-0.69
sigma-squared	0.15	15.14	0.14	5.77	0.14	5.95	0.21	2.34
gamma	0.99	1.E+03	0.99	2.E+02	0.99	6.E+06	0.99	6.E+04
LLF	22.70		-0.88		2.74		12.15	
LR test	123.55		118.73		115.22		102.44	
Mean Efficiency	0.65		0.59		0.61		0.66	

Note: * denotes vessel dummies in the technical efficiency model are not reported. $X_1 = engine\ power$, $X_2 = crew$, $X_3 = fishing\ days$, $Z_1 = storage\ capacity$, $Z_2 = quality\ control$, $Z_3 = vessel\ age$, $Z_4 = gear\ length$.

Source: Author's calculation

Table 2.7 **Hypothesis test for model specification: fish vessel**

Hypothesis	LR test	Critical value	Decision
1. $H_0 : \gamma = \delta_0 = \delta_1 = ... = \delta_4 = 0$ (No technical inefficiency)	58.25	$\chi^2_{.05(6)} = 12.592$	H_0 Rejected
2. $H_0 : \gamma = 0$ (Inefficiency effects are not stochastic)	58.25	$\chi^2_{.05(1)} = 2.706$	H_0 Rejected
3. $H_0 : \delta_0 = \delta_1 = ... = \delta_4 = 0$ (Inefficiency effects have a half-normal distribution)	30.4	$\chi^2_{.05(5)} = 11.070$	H_0 Rejected
4. $H_0 : \delta_1 = ... = \delta_4 = 0$ (Inefficiency effects have a truncated-normal distribution)	19.28	$\chi^2_{.05(4)} = 9.488$	H_0 Rejected
5. $H_0 : \delta_5 = ... = \delta_{11} = 0$ (Inefficiency effects do not come from vessels specific fixed effects)	7.64	$\chi^2_{.05(7)} = 14.067$	H_0 Accepted
6. $H_0 : \beta_t = \beta_{tt} = \beta_{nt} = 0$ (No technical change)	38.6	$\chi^2_{.05(5)} = 11.070$	H_0 Rejected
7. $H_0 : \beta_{tt} = \beta_{nt} = 0$ (Hick-neutral technical change)	33.52	$\chi^2_{.05(4)} = 9.488$	H_0 Rejected
8. $H_0 : \beta_{nm} = \beta_{tt} = \beta_{nt} = 0$ (Cobb Douglas production function)	53.94	$\chi^2_{.05(10)} = 18.307$	H_0 Rejected
9. $H_0 : \delta_4 = 0$ (Inefficiency effects do not come from gear length)	10.7	$\chi^2_{.05(1)} = 3.841$	H_0 Rejected
10. $H_0 : \delta_{storage\_capacity} = 0$ (Inefficiency effects do not come from storage capacity)	2.98	$\chi^2_{.05(1)} = 3.841$	H_0 Accepted

Source: Author's calculation

Table 2.8 **Model comparison-1: fish vessel**

	Model-1		Model- 2		Model-3		Model-4*	
	coefficient	t-ratio	coefficient	t-ratio	coefficient	t-ratio	coefficient	t-ratio
Production Function								
$Constant$	-0.97	-78.57	-1.58	-6.61	-1.50	-5.27	-0.84	-2.89
$\ln X_1$	-0.34	-1.41	-0.43	-1.97	-0.50	-3.39	-0.56	-2.13
$\ln X_2$	-1.48	-5.39	-0.75	-2.26	-0.72	-3.55	-1.53	-5.52
$\ln X_3$	1.61	3.54	0.32	0.49	0.76	1.19	2.01	3.12
$Year\_2004$	0.45	4.04	0.50	4.53	0.49	4.51	0.44	4.63
t	0.38	4.87	0.52	4.20	0.58	7.44	0.29	3.47
$\ln X_1 * \ln X_1$	0.26	3.84	0.06	0.65	0.11	1.03	0.28	5.18
$\ln X_1 * \ln X_2$	-0.86	-3.76	-0.30	-1.54	-0.40	-1.82	-0.92	-5.15
$\ln X_1 * \ln X_3$	0.05	0.41	-0.27	-0.49	-0.32	-4.33	-0.28	-0.59
$\ln X_2 * \ln X_2$	-0.10	-0.82	-0.07	-0.55	-0.03	-0.39	-0.23	-2.55
$\ln X_2 * \ln X_3$	0.07	0.22	0.57	0.72	0.50	1.73	0.51	0.85
$\ln X_3 * \ln X_3$	-0.05	-0.24	-0.29	-1.07	-0.17	-0.51	0.23	0.72
t^2	-0.05	-6.42	-0.06	-3.50	-0.07	-9.08	-0.04	-4.66
$\ln X_1 * t$	0.03	1.07	0.02	0.39	0.02	1.01	-0.01	-0.37
$\ln X_2 * t$	0.12	3.92	0.16	2.87	0.15	4.93	0.16	4.98
$\ln X_3 * t$	-0.21	-12.27	-0.08	-0.94	-0.15	-2.36	-0.24	-4.27
Technical Efficiency Model								
$Constant$	-0.39	-0.69			-1.46	-25.70	-0.01	-0.02
$\ln Z_1$	1.25	19.54					1.36	2.44
$\ln Z_2$	0.78	7.70					0.12	0.16
D_market	1.39	2.83					0.98	1.30
$D\_ownership$	-1.78	-10.91					-0.99	-1.25
sigma-squared	0.66	20.62	0.42	5.22	0.91	3.56	0.35	3.94
gamma	0.99	1.E+07	0.99	2.E+04	0.99	2.E+05	0.99	2.E+03
LLF	0.93		-14.27		-8.71		4.75	
LR test	58.25		27.84		38.97		65.90	
Mean Efficiency	0.71		0.72		0.72		0.72	

Note: * denotes vessel dummies in the technical efficiency model are not reported. $X_1 = engine\ power$, $X_2 = crew$, $X_3 = fishing\ days$, $Z_1 = vessel\ age$, $Z_2 = gear\ length$

Source: Author's calculation

Table 2.9 **Model comparison-2: fish vessel**

	Model-5		Model- 6		Model-7		Model-8*	
	coefficient	t-ratio	coefficient	t-ratio	coefficient	t-ratio	coefficient	t-ratio
Production Function								
$Constant$	-0.48	-6.62	-1.05	-17.34	-1.23	-3.83	-0.69	-4.34
$\ln X_1$	-0.69	-3.83	-0.92	-5.26	-0.58	-1.48	-0.53	-6.83
$\ln X_2$	-0.76	-4.03	-0.19	-0.64	-1.10	-2.13	-1.48	-11.92
$\ln X_3$	1.19	5.31	0.19	2.94	1.17	1.53	2.45	6.01
$Year\_2004$	0.49	26.44	0.47	252.66	0.42	3.53	0.38	5.56
t			0.05	18.37	0.40	3.91	0.32	6.10
$\ln X_1 * \ln X_1$	0.17	6.29	0.03	0.69	0.19	0.76	0.29	13.32
$\ln X_1 * \ln X_2$	-0.83	-10.73	-0.94	-4.64	-0.74	-2.05	-0.91	-11.21
$\ln X_1 * \ln X_3$	-0.28	-0.77	0.17	0.61	-0.20	-0.49	-0.27	-2.21
$\ln X_2 * \ln X_2$	0.00	0.01	0.61	3.12	-0.05	-0.29	-0.25	-6.84
$\ln X_2 * \ln X_3$	0.28	0.63	0.06	0.13	0.50	0.84	0.60	3.51
$\ln X_3 * \ln X_3$	0.54	2.37	-0.51	-8.52	-0.19	-0.49	0.41	2.04
t^2					-0.05	-3.63	-0.05	-7.02
$\ln X_1 * t$					0.02	0.65	-0.01	-0.42
$\ln X_2 * t$					0.14	3.63	0.16	41.33
$\ln X_3 * t$					-0.18	-2.63	-0.26	-4.17
Technical Efficiency Model								
$Constant$	0.69	0.99	0.28	0.41	-0.36	-0.54	-0.31	-0.40
$\ln Z_1$							-0.41	-0.93
$\ln Z_2$	2.18	4.89	3.06	4.54	0.99	2.37	1.66	2.33
$\ln Z_3$	0.84	1.16	-0.93	-1.38			0.18	0.22
D_market	1.69	2.50	2.66	3.87	1.28	1.83	0.54	0.63
$D\_ownership$	-1.00	-1.28	-2.38	-3.01	-1.64	-2.35	-0.85	-0.95
sigma-squared	0.77	5.89	0.70	4.17	0.50	5.00	0.34	3.73
gamma	0.99	3.E+07	0.99	7.E+07	0.99	5.E+04	0.99	1.E+06
LLF	-18.37		-15.83		-4.42		6.24	
LR test	48.71		42.05		47.55		68.87	
Mean Efficiency	0.62		0.58		0.69		0.73	

Note: * denotes vessel dummies in the technical efficiency model are not reported. $X_1 = engine\ power$, $X_2 = crew$, $X_3 = fishing\ days$, $Z_1 = storage\ capacity$, $Z_2 = vessel\ age$, $Z_3 = gear\ length.$

Source: Author's calculation

Table 2.10 **Main results: shrimp vessel**

	Model 1: Translog*				Model 1: Cobb-Douglas*			
	OLS		MLE		OLS		MLE	
	coefficient	t-ratio	coefficient	t-ratio	coefficient	t-ratio	coefficient	t-ratio
Production Function								
$Constant$	-0.37	-1.45	0.73	4.88	-0.73	-5.81	-0.81	-5.06
$\ln X_1$	0.12	0.48	-0.25	-2.36	0.24	4.41	0.22	3.59
$\ln X_2$	0.67	3.59	1.20	99.12	-0.11	-2.82	-0.19	-5.14
$\ln X_3$	1.17	3.25	1.52	8.47	0.68	6.31	0.40	2.32
$Year\_2004$	0.24	2.27	0.05	1.74	0.21	1.70	0.15	0.94
t	-0.05	-0.56	-0.28	-7.81	-0.05	-2.21	-0.02	-0.83
$\ln X_1 * \ln X_1$	-0.11	-1.05	0.06	5.64				
$\ln X_1 * \ln X_2$	0.10	1.46	-0.22	-11.40				
$\ln X_1 * \ln X_3$	0.80	4.13	-0.16	-2.53				
$\ln X_2 * \ln X_2$	0.20	3.65	0.36	10.89				
$\ln X_2 * \ln X_3$	-0.44	-2.33	0.12	1.56				
$\ln X_3 * \ln X_3$	0.23	1.87	0.30	13.43				
t^2	0.01	0.55	0.02	27.48				
$\ln X_1 * t$	0.04	1.62	0.04	5.44				
$\ln X_2 * t$	-0.05	-3.04	-0.06	-5.83				
$\ln X_3 * t$	0.17	3.17	-0.14	-8.41				
Technical Efficiency Model								
$Constant$			-2.45	-3.82			-0.58	-0.77
$\ln Z_1$			1.97	6.39			-0.02	-0.04
$\ln Z_2$			-1.51	-118.02			-0.49	-1.48
$\ln Z_3$			0.08	1.22			0.59	0.80
$\ln Z_4$			-3.05	-15.60			-0.35	-0.79
D_market			0.55	1.02			0.73	0.66
$D\_ownership$			-1.37	-3.48			-1.19	-1.55
sigma-squared	0.12		0.15	15.14	0.23		0.19	3.88
gamma			0.99	1.E+03			0.31	2.10
LLF	-39.07		22.70		-81.99		-54.60	
LR test			123.55				54.77	
Mean Efficiency			0.65				0.76	

Note: * denotes vessel dummies in the technical efficiency model are not reported. $X_1 = engine\ power$, $X_2 = crew$, $X_3 = fishing\ days$, $Z_1 = storage\ capacity$, $Z_2 = quality\ control$, $Z_3 = vessel\ age$, $Z_4 = gear\ length$.

Source: Author's calculation

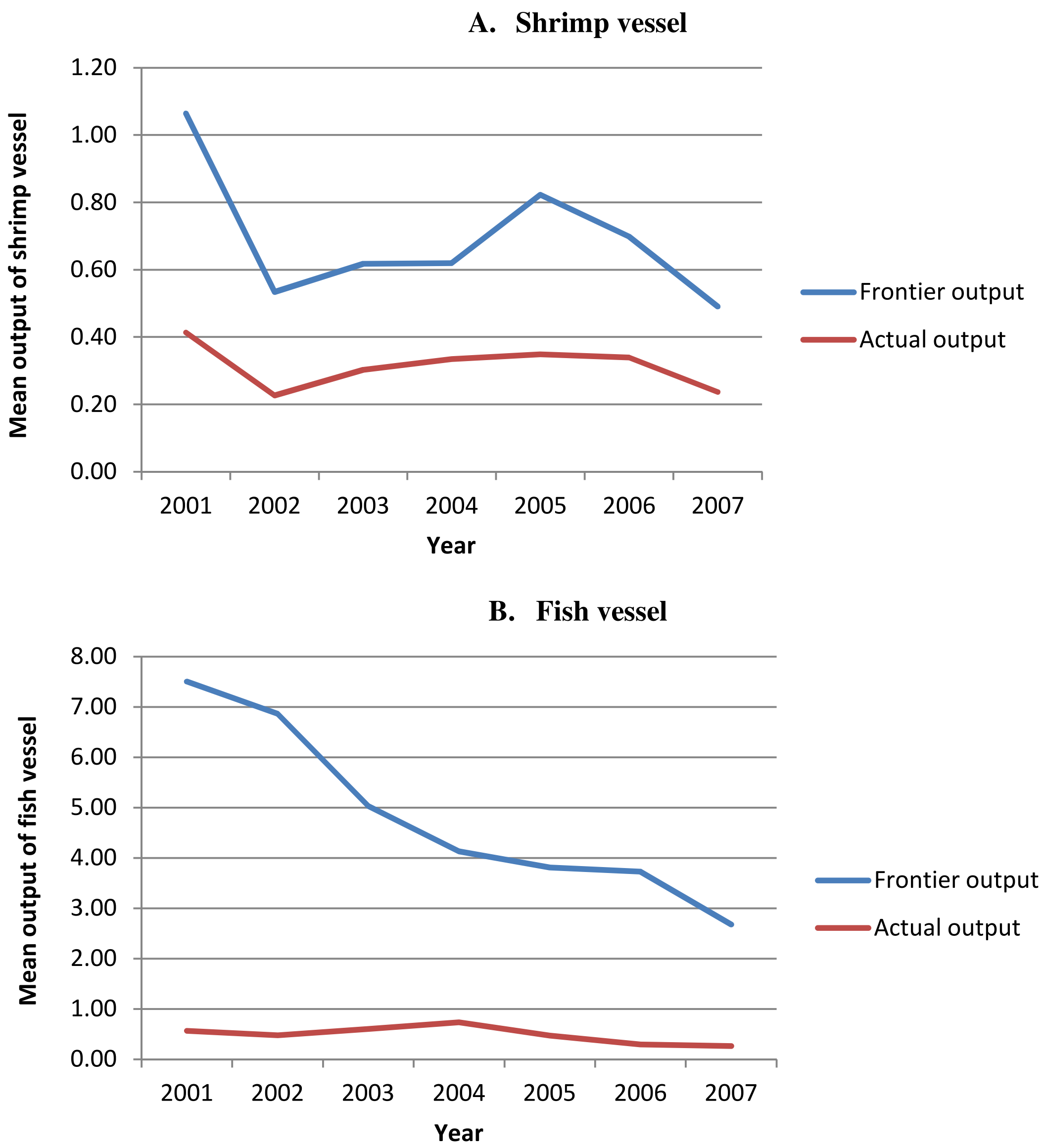
Table 2.11 **Main results: fish vessels**

	Model 1: Translog				Model 1: Cobb-Douglas			
	OLS		MLE		OLS		MLE	
	coefficient	t-ratio	coefficient	t-ratio	coefficient	t-ratio	coefficient	t-ratio
Production Function								
$Constant$	-0.31	-0.52	-0.97	-78.57	0.17	0.80	0.72	25.79
$\ln X_1$	0.28	0.58	-0.34	-1.41	0.13	1.73	0.02	2.87
$\ln X_2$	-0.97	-1.55	-1.48	-5.39	-0.34	-3.06	0.15	5.90
$\ln X_3$	2.83	2.43	1.61	3.54	1.32	4.92	0.21	6.64
$Year\_2004$	0.62	2.54	0.45	4.04	0.99	4.87	0.52	13.63
t	0.35	1.77	0.38	4.87	-0.11	-3.25	-0.19	-24.44
$\ln X_1 * \ln X_1$	-0.02	-0.09	0.26	3.84				
$\ln X_1 * \ln X_2$	0.29	0.65	-0.86	-3.76				
$\ln X_1 * \ln X_3$	-0.14	-0.43	0.05	0.41				
$\ln X_2 * \ln X_2$	-0.19	-0.86	-0.10	-0.82				
$\ln X_2 * \ln X_3$	0.06	0.12	0.07	0.22				
$\ln X_3 * \ln X_3$	0.71	1.10	-0.05	-0.24				
t^2	-0.05	-2.06	-0.05	-6.42				
$\ln X_1 * t$	0.06	1.54	0.03	1.07				
$\ln X_2 * t$	0.12	2.24	0.12	3.92				
$\ln X_3 * t$	-0.26	-1.92	-0.21	-12.27				
Technical Efficiency Model								
$Constant$			-0.39	-0.69			-11.83	-1.38
$\ln Z_1$			1.25	19.54			-6.77	-1.26
$\ln Z_2$			0.78	7.70			4.50	1.36
D_market			1.39	2.83			-13.19	-1.51
$D\_ownership$			-1.78	-10.91			1.37	1.28
sigma-squared	0.22		0.66	20.62	0.25		10.20	1.48
gamma			0.99	1.E+07			0.99	1.E+05
LLF	-28.20		0.93		-37.65		-26.04	
LR test			58.25				23.23	
Mean Efficiency			0.71				0.64	

Note: $X_1 = engine\ power, X_2 = crew, X_3 = fishing\ days, Z_1 = vessel\ age, Z_2 = gear\ length$
Source: Author's calculation

Appendix B: Figure

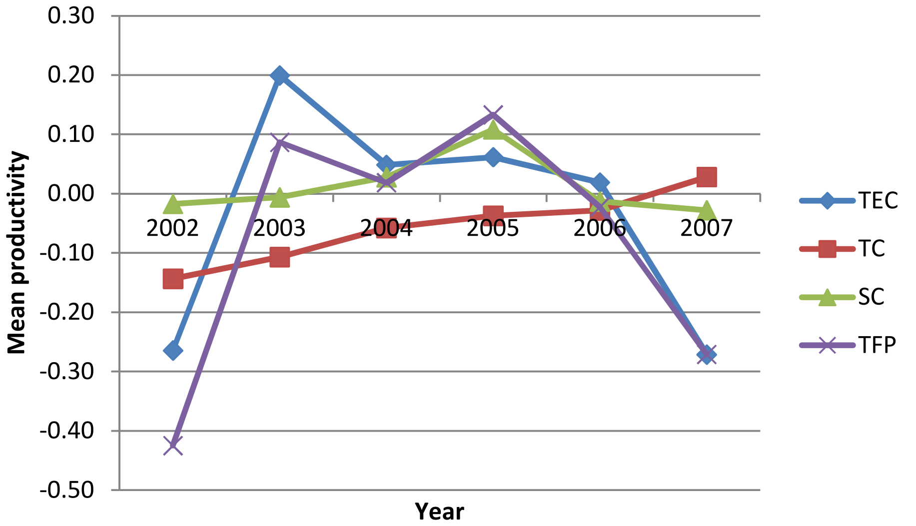
Figure 2.3 **Frontier output and actual output over time**



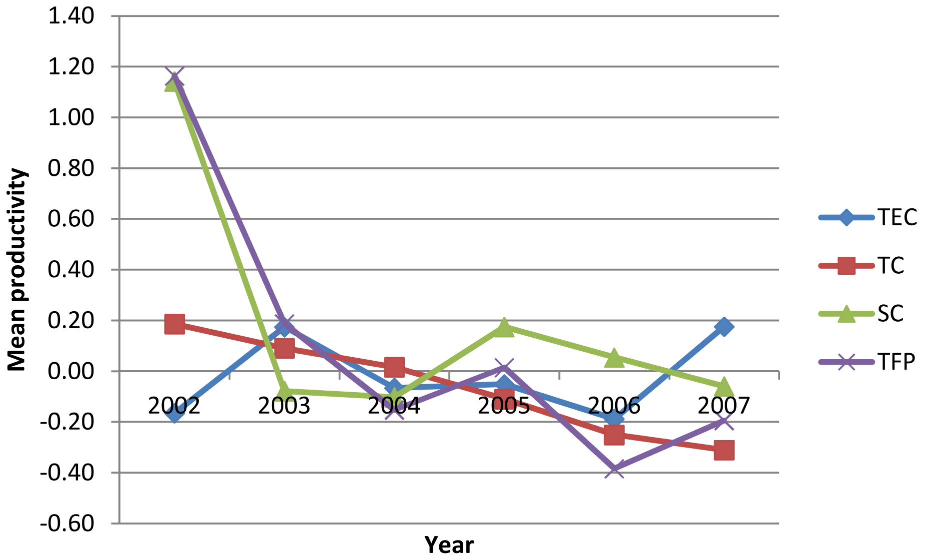
Source: Author's calculation

Figure 2.10 **Total Factor Productivity (TFP) over time**

A. Shrimp vessel



B. Fish vessel



Source: Author's calculation

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Chapter 3

Biomass dynamic models for industrial marine fisheries of Bangladesh

3.1 Introduction

Renewable natural resources, such as fish stock can be a sustainable natural resource and have long been an important source of food and other products for people and animals (Hartwick & Olewiler 1998). Fish stock is affected by various activities. Fishing activities are one of these by which fish stocks are affected to an increasing extent. Fishing is a typically important activitiy in developing economies compared to developed economies in terms of both small-scale personal consumption and large-scale commercial fishing. Social well-being of the harvester and the economic success of fishing industries totally depend on the state of fish stock. Success of fisheries, including the resource conservation and long-term social and economic interests, depends on the state of fish stocks (Gulland 1983). The state of fish stocks provides indicators to the decision-makers/managers to support rational choices and guide decision-makers/managers to decide whether an increase or decrease of effort is needed and how urgently action needs to be taken. The state of fish stocks also provides the past and current status of fish stock and provides the basis for applying harvest control rules and hence providing resources management advice.

The management of fish stocks is different to other agricultural resources, such as domestic stocks. Signalled by a drop in catches in a specific fishery, the government/fishery managers take necessary actions by introducing specific regulations to counteract overfishing so that the stock can be rebuilt. Different management tools[42] are considered to maintain healthy fish stock and healthy fishing industry and the choice of best management tool depends on the information on stock (Cooper n.d.). The effects of fishing on the stocks and on the catch are important management issues. For instance, in a trawl fishery the use of an appropriate size of mesh in the cod-end allows the small fish to escape, but the enforcement causes difficulties to the fishers who fish for smaller

[42] Quotas, size limits, gear restrictions, season limits and area closures.

species. In addition, without taking appropriate measures, increasing additional effort in the fishery would cause the significant rise in the catch rate and tends to reduce the stock, hence falls in catch rates are sustained. On the other hand, there are some other factors that considerably influence the catch rate and in most cases, these influences are greater on the catch rate than the overall abundance of stock. These factors are mainly the size of trawler, the skill of the skipper, the precise ground, the season, the weather and the time of the day of fishing (Gulland 1983). In addition, the catch rate is also influenced by types of fishing patterns. For instance, two different patterns of fishing such as trawl with large and small meshes in the cod-end, also make huge differences to the catch in particular years.

To make the resource available in the future, most management measures are concerned with controls on the current fishery. A common and traditional objective of management is to maintain Maximum Sustainable Yield (MSY). MSY gives a useful description of fish stocks and contains three different ideas such as maximizing quantity, ensuring sustainability and the physical yield that is being an appropriate measure of the well-being of a fishery. The concept of MSY serves as the foundation of most biological reference points, which give decision-makers guidance in determining whether stocks are too small or fishing pressure is too great. If the abundance of stock is above MSY, the stock is considered under-exploited; if below MSY, the stock is overfished and management actions are urgently needed. If the stock is the same as MSY, then the fishery looks well (Gulland 1983). MSY provides quantitative values of targets and thresholds (Cooper n.d.). Targets are values for stock size and fishing mortality rates that managers aim to achieve and maintain. Targets are determined by a combination of biological and socio-economic factors, where the optimum yield (the amount of catch) is important in providing overall long-term benefits to the society. On the other hand, thresholds are referred to limits, which are defined as specific fishing mortality rate or stock size that is some fraction of MSY. Overfishing occurs when the fishing mortality rate exceeds a specific threshold, while a stock is determined to be overfished when stock size falls below a specific threshold. If a stock is overfished, or, if overfishing is occurring, managers are required to put measures in place to correct the situation. In order to manage stock, decision-makers define a stock size threshold, which can be defined in one of two ways: the stock size threshold may be defined either as a percentage of MSY, normally half of MSY, but never less than half; or, the smallest stock size that could grow to MSY in ten years, if the fishing mortality rate is as low as possible (Cooper n.d.). The MSY is developed and applicable to spawner-recruit models, surplus production models, delay-difference models, age-structured and size-structured models and so on (e.g., Getz & Haight 1989; Hilborn & Walters 1992; Quinn & Deriso 1999). In the absence of information on age or length structure, surplus production models are used and the analyses are done based on effort and catch data (e.g., Chen & Andrew 1998; Hilborn & Walters 1992).

The objective of this study is to estimate biological reference points of industrial marine fisheries of Bangladesh in order to find out the current status of the industrial marine fisheries. A number of surveys have been conducted in the marine waters of the Bangladesh continental shelf and these surveys were conducted to assess the stock of the marine resources during 1958-1984, which are considered as obsolete. These surveys identified various fishing grounds and made some assessment of the standing stock and potential catch in the marine sector. The area of these surveys was 10-100 metres depth within the EEZ of Bangladesh, and the surveys assessed the pelagic and demersal stocks. Signals of overfishing and stock exhaustion are noticeable and reported from artisanal capture fisheries (FAO 2006). Controversy exists about the extent of fish resources, and whether the marine fisheries are under or over-exploited within the EEZ of Bangladesh. Alam & Thomson (2001) expressed their concern over whether or not marine fisheries are over-exploited in Bangladesh. The World Bank (1991) believes that marine fisheries of Bangladesh have reached a maximum sustainable level and there is limited scope for expansion. According to the annual report (2007) published by the Department of Fishery (DoF), marine shrimp fishery is over-exploited as almost all fishermen have reported a serious decline in their catch and some have shifted from their preferred catches to other species in order to continue fishing. DoF's report (2007) highlights that marine fish fishery is under-exploited due to knowledge and information on the availability of the sizes of different fish stocks and partly due to the lack of technological developments for harvesting the new resources. A need for new surveys and new information to prescribe a rational management strategy is highlighted in DoF's report (2007). No literature is found that describes surveys that have been done separately for artisanal fisheries and industrial fisheries.

This is the first kind of study that covers beyond 40 metres depth within the EEZ of Bangladesh to estimate biological reference points and to measure the current status of industrial marine fisheries. The biological reference points of this study are measured using biomass dynamic models: a dynamic version of surplus production models and a time series data for the period 1992-2007 is used. This is the first kind of study of the industrial marine shrimp and fish fisheries in Bangladesh, where Clarke, Yoshimoto & Pooley (CY&P) models are used to apply the Ordinary Least Square (OLS) method and to calculate the biological parameters. Using these biological parameters the current abundance of biomass, biomass at MSY and the biomass at the steady-state are measured. The study shows that the shrimp stock of the industrial marine fisheries is over-exploited and the fall in catch per unit effort (CPUE) over time of the industrial marine shrimp fishery is due to the fall in stock size. On the other hand, the fish stock of the industrial marine fisheries is under-exploited and the fall in CPUE over time of the industrial marine fish fishery is due to inadequate knowledge and information on the availability of the sizes of different fish stocks and lack of technological developments for harvesting the new resources. The study also shows that to maintain steady-state equilibrium and adequate growth rate of both shrimp and fish, fishing patterns need to be modified. The study also indicates that the current management system fails to increase the level of high-valued shrimp stocks and to increase the catch level of the low-valued stocks.

The remainder of this chapter is divided into four sections. Section 3.2 presents the theoretical framework followed by data and variables in Section 3.3. Section 3.4 presents the models for both shrimp and fish stocks including the discussion of the results. Section 3.5 concludes the paper.

3.2 Theoretical framework

Considering the importance of population dynamics and stock assessment in fisheries management, fisheries management modeling was introduced in the early 20th century. Fishery models are mainly about the population dynamics of single-species and have gradually expanded to take account of externalities and linked bio-physical, socio-economic and governance systems. According to the Smith & Fulton (2010), the first model was introduced by Baranov (1914) and extended by Graham (1935). Then a series of papers contributed to the fisheries management modeling (Beverton & Holt 1957; Ricker 1954; Schaefer 1954) and economic considerations were taken into account in the fisheries management modeling by Gordon (1954) in the same period.

All these models are classified as either holistic or analytical. Holistic models assume that fish stock is a homogeneous biomass. These models do not consider length or age structure of the stock. Two simple methods are used in the literature: the swept area method and the surplus production model. The swept area method is based on research trawl survey catches per unit of area. The surplus production model uses catch per unit of effort as input. The model assumes that the biomass of fish is proportional to the catch per unit of effort. Production models are the simple models in where analysis is done with little information, such as catch, abundance and amount of fishing. These models are suitable in the absence of information on age or length structure (e.g., Chen & Andrew 1998; Hilborn & Walters 1992). The detailed information (such as growth of individual fish, mortality due to fishing, natural causes (disease, predation and so forth) and reproduction), which determines the increase and decrease in abundance of fish stocks, can be incorporated in a group of separate models. These models allow the parameters to vary in accordance with the density of stocks, which are more complex and known as analytical models. Analytical models have been developed by Baranov (1914), Thompson & Bell (1934) and Beverton & Holt (1956). These models require the age composition of catches and are age-structured models[43] which use mortality rates and individual body growth rates. Based on holistic and analytical models different fisheries assessment models are used such as the production model, spawner-recruitment model, simulation model, sequential population assessment model (VPA and/or cohort analysis), delay-difference models, age-structured model, size-structured model and dynamic pool model (such as yield-per-recruit model) (e.g., Getz & Haight 1989; Hilborn & Walters 1992; Quinn & Deriso 1999).

All models, both holistic and analytical, mainly deal with a single target species exploited by a single-fleet (e.g., Funk et al. 2000; Hilborn & Walters 1992; Motos & Wilson 2006). Multi-species fisheries models in fisheries management are very recent concepts and were introduced between the 1970s and 1980s using several approaches. Of these, some are an extension of predator-prey models (e.g., Beddington & May 1982; May et al 1979). Others relate to the concept of natural mortality in the existing single-species models (e.g., Helgason & Gislason 1979; Pope 1979). A few models consider broader trophic and eco-system properties of fishery systems (e.g., Bax 1985;

[43] The concept in the age-structured model is that of a cohort. A cohort of fish is a group of fish all the same age belonging to the same stock (Sparre & Venema 1998). If the fish are caught too young there is a growth overfishing of the stock. Two major elements describe the dynamics of a cohort. The first element is the average body growth in length and weight and the second element is the death process.

Laevastu & Larkins 1981; Polovina 1984). Very few early models consider practical fisheries assessment and management (Smith & Fulton 2010). One of the most influential multi-species models was introduced by Anderson & Ursin (1977) and used by the International Council for the Exploration of the Sea (ICES) Multi-species Working Group (Pope 1991). Then the multi-species VPA approach was developed (Sparre 1991).

Sparre & Venema (1998) argued that many aspects of the models for a multi-species or multi-fleet are yet to be investigated and/or understood. A few multi-species or multi-fleet models based on dynamic pool models (also known as Beverton and Holt's yield-per-recruit model) are either length-structured[44] or age-structured (e.g., Ye 1998). A multi-species mortality model for dynamic pool models is suggested in Sparre & Venema (1998), which estimates fishing mortalities for two species. Recent models on multi-species and multi-fleet have been developed based on VPA analysis and used simulation tools[45]. Thompson & Bell (1934) used aged-based single-species analysis for fleet. The dynamics of fleet for stock assessment through dynamic pool models are not widely used and the associated literature is also limited. Models dealing with multi-fleet and/or multi-species for stock assessment are very limited[46]. A multi-fleet mortality model for the dynamic pool model is found in Garcia & von Zalinge (1982), which estimates one species (shrimp). Kompas et al (2010) describe technical interactions of two fleets between two tiger species and two endeavor species under the Australian Northern Prawn Fishery using spawner stock and recruitment models. Kompas & Che (2006) use the population dynamics of growth-length relationship for a multi-species and multi-fleet Western and Central Pacific tuna fishery.

The age and length structure of industrial marine fisheries of Bangladesh are unknown, hence this study uses biomass dynamic models: a dynamic version of surplus production models. Biomass dynamic models apply the basic population dynamics model to data on catches. The two dominant variables for biomass dynamic models are carrying capacity and the intrinsic growth rate. Targets and thresholds derived from biomass dynamic models are almost completely predetermined by the choice of model structure and the values of carrying capacity and intrinsic growth rate. Common

[44] For example, Chen & Gordon 1997; Nedreaas et al 1996; Sainsbury 1984; Shephard 1988; Spencer et al 2002.
[45] For example, Drouineau et al 2006; Mahevas & Pelletier 2004; Ulrich et al 2002.
[46] For example, Kompas et al (2010); Kompas & Che (2006).

density-dependent models include Schaefer (or, Graham-Schaefer) model and the Gompertz-Fox models. Other models, such as the Pella-Tomlinson model are somewhat more flexible, because they add parameters to describe how the growth rate changes with respect to stock size. But, the values of targets and thresholds in the Pella-Tomlinson model are no less sensitive to errors and biases in carrying capacity or intrinsic growth rate than the more common density-dependent models.

The fitted biomass dynamic model that is used in this study is:

$$B_{t+1} = B_t + g(B_t) - C_t \tag{3.1}$$

B_t is the biomass at the start of year t; C_t is the catch in weight during year t and $g(B_t)$ is the biomass-dynamic as a function of biomass.

According to the Clarke et al (1992), five different models are found for $g(B_t)$ to describe the biological production relationship: the Schaefer model (1957), the Fox model (1970), the Schnute model (1977), which is a modified version of the Schaefer model, a threshold model by Sathiendrakumar & Tisdell (1987), and the CY&P model (1992), which is a modified version of the Fox model. These models are different in terms of different production relationships. The Schaefer and Schnute models show parabolic/logistic relation between yield and effort; the Fox and CY&P models show Gompertz curve (Richards 1959) and the threshold model has a logarithmic relation between yield and effort. The Schaefer, Schnute, Fox and CY&P models describe the relation between stock size, fishing effort and yield to one another (Clarke et al 1992), which are derived from generalized stock production model (Pella & Tomlinson 1969):

$$\frac{dB}{dt} = rB - \left(\frac{r}{K}\right)B^m - C \tag{3.2}$$

$\frac{dB}{dt}$ is the growth rate of biomass; r is the intrinsic growth; B is the current biomass; K is the maximum stock level or virgin biomass and C is the catch rate. Based on the value of m, the growth rate follows either logistic or Gompertz curve. When $m = 2$, the growth rate is logistic:

$$\frac{dB}{dt} = rB\left(1 - \frac{B}{K}\right) - C \tag{3.3}$$

and when $m \to 1$ the growth rate follows Gompertz curve:

$$\frac{dB}{dt} = rB\ln\left(\frac{K}{B}\right) - C \tag{3.4}$$

The difference between Equation 3.3 and 3.4 is the logistic growth is symmetrical, while the Gompertz is an extreme case and shows a potential extinction of the fishery (Clarke et al 1992).

The catch rate in Equation 3.2 is:

$$C = qEB \tag{3.5}$$

Where, q is the catchability coefficient, E is effort and B is biomass. Using Equation 3.5, catch per unit effort (CPUE) can be defined as:

$$U = \frac{C}{E} \tag{3.6}$$

Thus, the biomass can be written in terms of CPUE as:

$$B = \frac{U}{q} \tag{3.7}$$

Using biomass Equation 3.7 and multiplying both sides of Equation 3.4 by $\frac{q}{U}$ the growth rate can be written in terms of CPUE as:

$$\frac{1}{U}\frac{dU}{dt} = r\ln(qK) - r\ln(U) - qE \tag{3.8}$$

To solve Equation 3.8, finite difference approximation is used by Schaefer (1957) and Fox (1970) models; Schnute (1977) develops a modified version of the Schaefer (1957) model and uses integration procedure; CY&P (1992) model applies a similar approach to the Fox (1970) model and uses Taylor approximation. After the approximation, in all models the Ordinary Least Square (OLS) technique is applied to estimate parameters r, q and K.

This study uses the CY&P (1992) model for both shrimp and fish fisheries, which is associated with the biological production relationship of the Gompertz curve described in Equation 3.4. The CY&P (1992) model incorporates a non-linear assumption and has a good fit to the limited time series data. Following Appendix A of the Clarke et al (1992), the CY&P (1992) model for this study can be written as:

$$\ln\left(\overline{U_{t+1}}\right)=\left(\frac{2r}{2+r}\right)\ln(qK)+\left(\frac{2-r}{2+r}\right)\ln\left(\overline{U_t}\right)-\left(\frac{q}{2+r}\right)\left(\overline{E_t}+\overline{E_{t+1}}\right) \tag{3.9}$$

Equation 3.9 can be simplified as follows and the OLS technique can be applied to the equation:

$$\ln\left(\overline{U_{t+1}}\right)=c_1+c_2\ln\left(\overline{U_t}\right)+c_3\left(\overline{E_t}+\overline{E_{t+1}}\right) \tag{3.10}$$

From Equation 3.10, three parameters $r=\frac{2(1-c_2)}{(1+c_2)}$, $q=-c_3(2+r)$ and $K=\frac{e^{\frac{c_1(2+r)}{2r}}}{q}$ can be estimated.

The results depend on how good an approximation the Taylor polynomial gives. If instantaneous values of CPUE for a given year, t, are suspected to fluctuate considerably away from $\overline{U_t}$, the Taylor approximation becomes invalid and another method to estimate the integral of $\ln(U)$ is needed (Clarke et al 1992).

Using the estimated values of the parameters r, q and K, the current abundance of biomass, biomass at MSY and biomass at steady-state, can be estimated. Both catch and effort at the MSY and at the steady-state also can be estimated.

3.3 Data and variables

Either fishery-dependent[47] or fishery-independent[48] data can be used for stock assessment (Cooper n.d.). In this study, fishery-dependent data is used and collected from the fishing log books from the Marine Fisheries Department (MFD) under the Department of Fishery (DoF) of Bangladesh. A time series data for the period 1992-2007 is used in this study.

The Bangladesh coastline extends for 714 km with an Exclusive Economic Zone (EEZ) of 166,000 square km of which 44 percent is continental shelf. The marine water extends beyond the continental shelf, measuring 200 nautical miles from the base line (10 fathoms) including rivers and estuaries. Marine fisheries of Bangladesh consist of two fisheries: artisanal[49] fisheries and industrial[50] fisheries. Industrial fisheries are associated with open access and industrial fleets have been expanding over time (MFD 2009).

Industrial fishing vessels are divided into two broad categories: shrimp fleet and fish fleet. Vessels in the shrimp fleet are double-rigged vessels, fitted with two side beams from which two shrimp-trawl nets are simultaneously operated. A standard shrimp vessel is made of steel hull and the mesh size of the net at the cod-end is 45mm. Shrimp trawls occur beyond 40 metres depth within the EEZ of Bangladesh. On the other hand, vessels in the fish fleet are stern vessels with a single-rigged trawl-net operated behind the vessels and these vessels are smaller than shrimp vessels (MFD 2009). These vessels generally have both wooden and steel hulls and the mesh size of the net at the cod-end is 60mm. Fish trawls occur in four different fishing areas. Traditional fish trawls occur beyond 40 metres depth at high tide to catch fin fish and shrimp; modern fish trawls occur between 40 and 100 metres depth to catch fin fish; demersal trawls

[47] Fishery-dependent data are derived from the fishing process itself and are collected through such avenues as self-reporting, landing records, onboard observers, portside surveys, log book and vessel trip reports, telephone surveys or vessel-monitoring systems.
[48] Fishery-independent data are derived from activities that do not involve the commercial or recreational harvest of fish, such as trawl, acoustic, video and side-scan sonar research surveys and some tagging experiences. The majority of this sort of data comes from research surveys conducted by the government.
[49] The *artisanal fisheries* are small-scale onshore fishery and fishing occurs up to 40 metres depth with mechanized and non mechanized boats.
[50] The *industrial fisheries* are large-scale offshore fishery and fishing occurs beyond 40 metres depth within the EEZ of Bangladesh with industrial vessels.

occur between 100-200 metres depth to target demersal white fish and mid water trawls occur beyond 40 metres depth to catch mid water fish.

Commercially important fishery resources are normally harvested by the industrial fishing vessels. The key commercial marine shrimp species those are harvested by the industrial vessels are tiger shrimp (*Penaeus monodon*) and brown shrimp (*Metapenaeus monodon*). *Penaeus monodon* (tiger shrimp) is the most valuable and hence the targeted species. But the highest (almost two thirds of the total) contribution to the total catch is from *Metapenaeus monodon* (brown shrimp). On the other hand, more than ninety fish species are commercially important. These fall under the common group. The major commercial fin fish species exploited by the industrial vessels are pomfret (*Pampus argenteus*), goatfish (*Upenuus sulphureus*), bream (*N. japonicas*), lizard fish (*Saurida tumbil*), grunter (*Popmadasys hasta*), red snapper (*Lutjanus johnii*) and carangid (*Arioma indica*) (MFD 2009). According to the data of the Marine Fisheries Department (MFD) of Bangladesh between 2001 and 2007, the major amount of total targeted catches of shrimp comes from shrimp fleet (99.09 percent) and the amount of total targeted catches of fish comes from fish fleet (71.93 percent). The catch of shrimp and fish by different fleets in the period 2001-2007 is shown in Table 3.1.

Table 3.1 **Shrimp and fish catch by different fleets**

Year	Shrimp catch (tonnes)			Shrimp catch (%)		Fish catch (tonnes)			Fish catch (%)	
	Shrimp fleet	Fish fleet	Total	Shrimp fleet	Fish fleet	Fish fleet	Shrimp fleet	Total	Fish fleet	Shrimp fleet
2001	3156	15	3171	99.53	0.47	13180	6453	19633	67.13	32.87
2002	2769	23	2792	99.18	0.82	14820	4820	19640	75.46	24.54
2003	2616	42	2658	98.42	1.58	17158	7559	24717	69.42	30.58
2004	3061	8	3069	99.74	0.26	21122	7911	29033	72.75	27.25
2005	3266	9	3275	99.73	0.27	22505	8305	30810	73.04	26.96
2006	3398	41	3439	98.81	1.19	21890	7889	29779	73.51	26.49
2007	2146	39	2185	98.21	1.79	19662	7567	27229	72.21	27.79
Mean	2916	25	2941	99.09	0.91	18620	7215	25834	71.93	28.07

Source: Author’s calculation

Both shrimp and fish are demersal[51] resources of the industrial marine fisheries. The management conditions allow both shrimp and fish fleets to catch 30 percent of bycatch, but due to the use of different gear and mesh sizes, the average bycatch of both fleets, in fact, is very low. So, the bycatch of both shrimp fleet (28.73 percent fish) and

[51] Demersal and ground fish are those that feed on ocean or lake bottoms and typically do not range over a wide area.

fish fleet (0.91 percent shrimp) are ignored in this study and the targeted resources (shrimp and fish) are considered as homogeneous biomasses. On the other hand, both shrimp and fish fleets are operated with two different sets of gear: double riggers (for shrimp) and stern trawl (for fish) with 45mm and 60mm mesh sizes of the net at the cod-end, respectively. All vessels within the fleets are considered as homogeneous vessels in terms of gear. Both fleets are independent in their targeted catch. Hence, this study uses two different biomass dynamic models for both shrimp and fish fisheries by using two different CY&P (1992) models.

Catch per unit effort (CPUE) is used to estimate CY&P models for both shrimp and fish stocks. To estimate CPUE, catch and effort data are collected from MFD (2009). Catch data is measured in tonnes per year. The total catch for both shrimp and fish are calculated as:

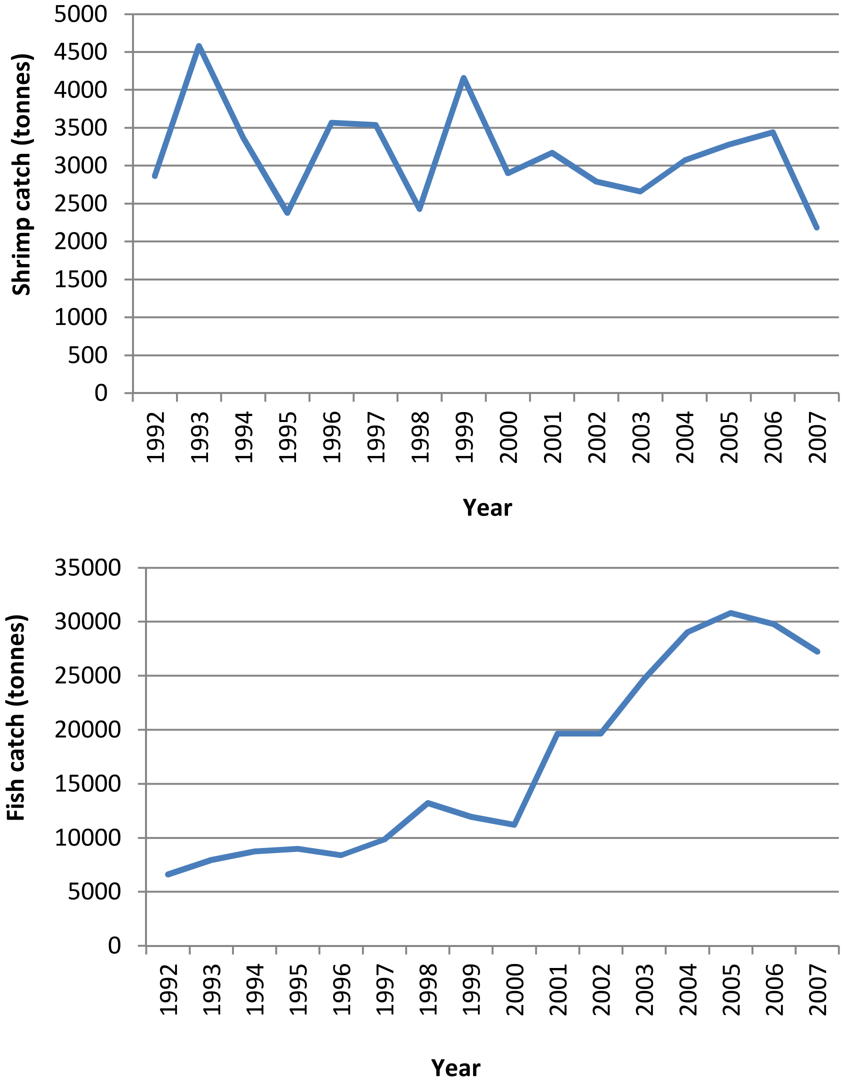
$$C_t^s = \sum_{i=1}^{n} c_{it}^s \tag{3.11}$$

$$C_t^f = \sum_{i=1}^{n} c_{it}^f \tag{3.12}$$

In Equation 3.11 and 3.12, s and f denote shrimp and fish, respectively; $i = 1,2,....,n$ number of vessels; $t = 1,2,....,n$ year; C_t^s is the total catch of shrimp in year t; $\sum_{i=1}^{n} c_{it}^s$ is the sum of the total catch of shrimp by all vessels in the shrimp fleet in year t; C_t^f is the total catch of fish in year t and $\sum_{i=1}^{n} c_{it}^f$ is the sum of total catch of fish by all vessels in the fish fleet in year t.

Data shows that between 1992 and 2007, there is a huge variation in catch between shrimp and fish fisheries. The amount of catch of shrimp varies from 2185 tonnes to 4579 tonnes per year with an average of 3148 tonnes per year, and the standard deviation is 638 tonnes. On the other hand, in the same period the amount of catch of fish varies from 6621 tonnes to 30810 tonnes per year with an average of 16730 tonnes and the standard deviation is 8935 tonnes. The trends of total catches of both shrimp and fish in the period 1992-2007 are shown in Figure 3.1.

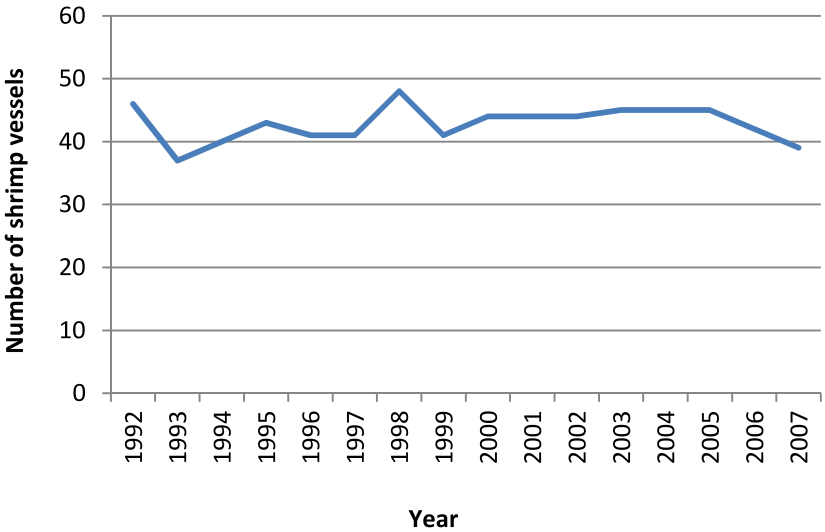
Figure 3.1 **Trend of total catches of shrimp and fish over time (1992-2007)**

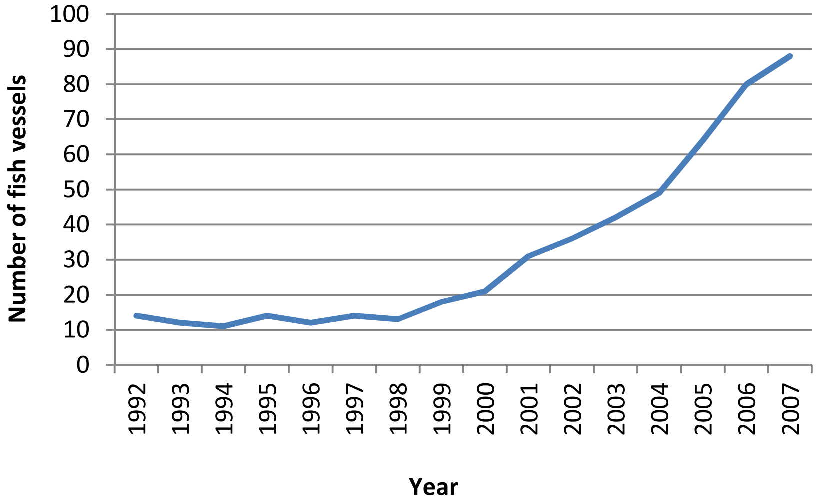


Source: Author's calculation

Figure 3.1 shows that the trend of shrimp catch is decreasing overall, while the trend of fish catch shows a sharp increase over time. The sharp increase in fish catch may be due to the increase in the number of fish vessels over time, which is shown in Figure 3.2.

Figure 3.2 **Number of shrimp and fish vessels over time (1992-2007)**





Source: Author's calculation

Between 1992 and 2007, an average of 43 shrimp vessels per year are engaged in fishing, which varies from 37 to 48 vessels per year and the standard deviation is 3 vessels. In the same period, fish vessels that are engaged in fishing vary from 11 to 88 vessels per year with an average of 32 vessels and the standard deviation is 26 vessels. The total vessels engaged in fishing between 1992 and 2007 vary from 49 to 127 with an average of 75 vessels per year and the standard deviation is 26.

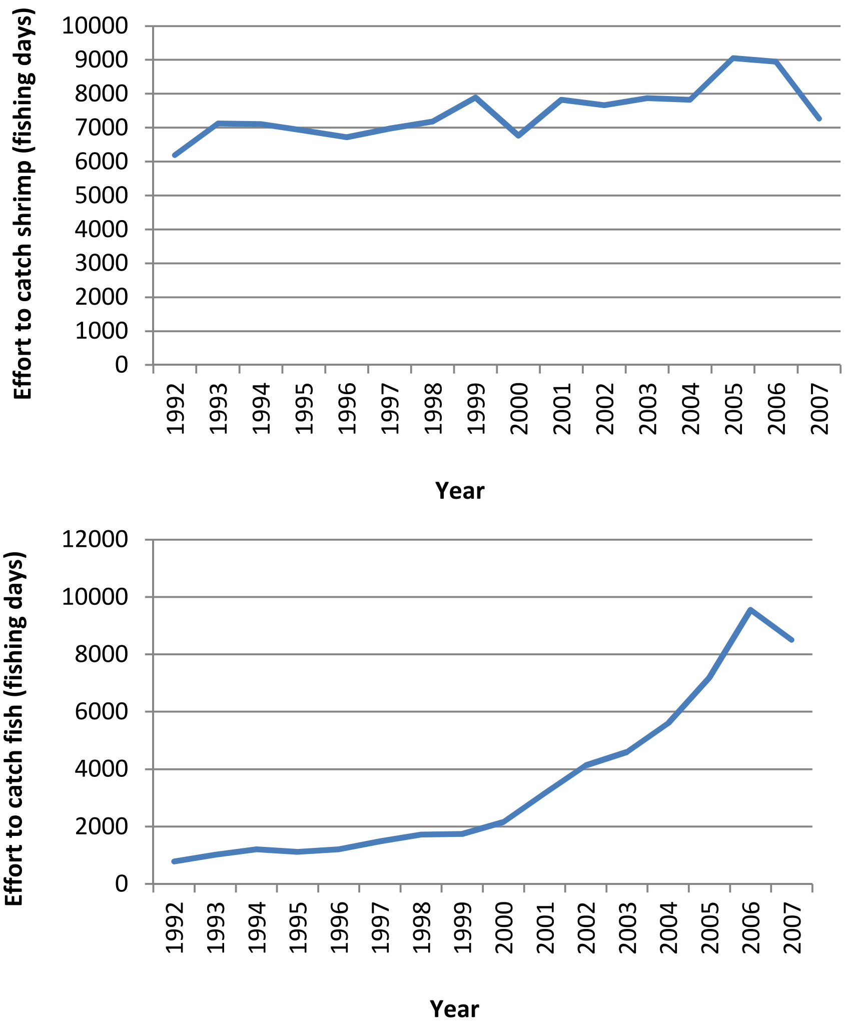
Effort data is measured in fishing days per year. The total effort to catch both shrimp and fish is calculated as:

$$E_t^s = \sum_{i=1}^{n} e_{it}^s \tag{3.13}$$

$$E_t^f = \sum_{i=1}^{n} e_{it}^f \tag{3.14}$$

In Equation 3.13 and 3.14, s and f denotes shrimp and fish, respectively; $i = 1,2,....,n$ number of vessels; $t = 1,2,....,n$ year; E_t^s is the total fishing days to catch shrimp in year t; $\sum_{i=1}^{n} e_{it}^s$ is the sum of total fishing days to catch shrimp by all vessels in the shrimp fleet in year t; E_t^f is the total fishing days to catch fish in year t and $\sum_{i=1}^{n} e_{it}^f$ is the sum of total fishing days to catch fish by all vessels in the fish fleet in year t. The trends of total effort to catch both shrimp and fish in the period from 1992 to 2007 are shown in Figure 3.3.

Figure 3.3 **Trend of total effort to catch shrimp and fish over time (1992-2007)**



Source: Author's calculation

Figure 3.3 shows that the trend of total effort to catch both shrimp and fish is increasing, but the trend of effort to catch fish shows a sharp increase over time. The sharp increase in fish catch may also be due to the increase in the number of fish vessels over time, which is shown in Figure 3.2.

Data shows that between 1992 and 2007, effort data varies between shrimp and fish fisheries. Between 1992 and 2007, the total effort that is used to catch shrimp species varies from 6191 days to 9050 days per year with an average of 7457 days per year, and the standard deviation is 772 days per year. On the other hand, in the same period the amount of effort that is used to catch fish species varies from 781 days to 9553 days per year with an average of 3447 days and the standard deviation is 2866 days.

Catch per unit effort for both shrimp and fish are calculated as:

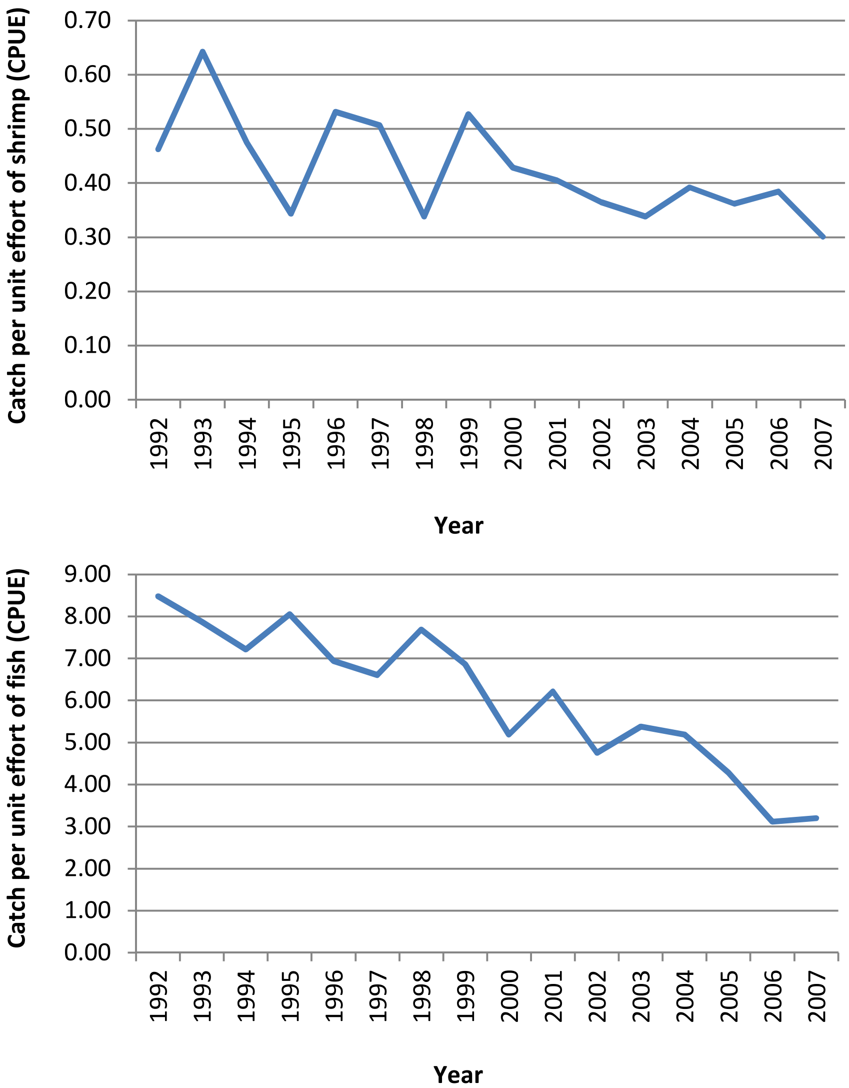
$$U_t^s = \frac{\sum_{i=1}^{n} c_{it}^s}{\sum_{i=1}^{n} e_{it}^s} \tag{3.15}$$

$$U_t^f = \frac{\sum_{i=1}^{n} c_{it}^f}{\sum_{i=1}^{n} e_{it}^f} \tag{3.16}$$

In Equation 3.15 and 3.16, $i = 1,2,....,n$ number of vessels; $t = 1,2,....,n$ year; U_t^s is the catch per unit effort for shrimp in year t ; $\sum_{i=1}^{n} c_{it}^s$ is the sum of total catch of shrimp by all vessels in shrimp fleet in year t; $\sum_{i=1}^{n} e_{it}^s$ is the sum of total fishing days to catch shrimp by all vessels in shrimp fleet in year t; U_t^f is the catch per unit effort for fish in year t; $\sum_{i=1}^{n} c_{it}^f$ is the sum of total catch of fish by all vessels in fish fleet in year t; $\sum_{i=1}^{n} e_{it}^f$ is the sum of total fishing days to catch fish by all vessels in fish fleet in year t.

Data shows that between 1992 and 2007, there is a huge variation in catch per unit effort between shrimp and fish fisheries. The catch per unit effort for shrimp species varies from 0.30 to 0.64 with an average of 0.43, and the standard deviation is 0.09. On the other hand, in the same period the catch per unit effort for fish species varies from 3.12 to 8.48 with an average of 6.07 and the standard deviation is 1.68. The trends of catch per unit effort for shrimp and fish in the period 1992-2007 are shown in Figure 3.4.

Figure 3.4 **Trend of total CPUE for shrimp and fish over time (1992-2007)**



Source: Author's calculation

Figure 3.4 shows that the trend of catch per unit effort (CPUE) of both shrimp and fish is decreasing over time, but the trend of CPUE of fish shows a sharp decrease compare to the CPUE of shrimp. The sharp decrease in CPUE of fish may be due to the increase in ther number of fish vessels over time, which is shown in Figure 3.3. On the other hand, according to the Department of Fisheries' annual report (2007), decline in shrimp catch is may be due to overexploitation of the marine shrimp fishery, while the report highlights that the marine fish fishery is under-exploited due to knowledge and information on the availability of the sizes of different fish stocks and partly due to lack of technological developments for harvesting the new resources.

The summary statistics of catch, effort and CPUE are shown in Table 3.2.

Table 3.2 **Summary statistics: catch, effort and CPUE**

Variable	Unit		Minimum	Maximum	Mean	Standard Deviation
Catch	Tonnes per year	Shrimp	2185	4579	3148	638
		Fish	6621	30810	16730	8935
Effort	Fishing days per year	Shrimp	6191	9050	7457	772
		Fish	781	9553	3447	2866
CPUE	Tonnes per fishing days	Shrimp	0.30	0.64	0.43	0.09
		Fish	3.12	8.48	6.07	1.68

Source: Author's calculation

3.4 Models and Results

The biomass dynamic models for both shrimp and fish are estimated using CY&P models. The CY&P (1992) model is estimated for a shrimp fishery:

$$\ln\left(\overline{U_{t+1}^{s}}\right)=\left(\frac{2r_s}{2+r_s}\right)\ln\left(q_s K_s\right)+\left(\frac{2-r_s}{2+r_s}\right)\ln\left(\overline{U_t^{s}}\right)-\left(\frac{q_s}{2+r_s}\right)\left(\overline{E_t^{s}}+\overline{E_{t+1}^{s}}\right) \tag{3.17}$$

and the OLS technique for the shrimp fishery is applied to the following equation:

$$\ln\left(\overline{U_{t+1}^{s}}\right)=c_1^s+c_2^s\ln\left(\overline{U_t^{s}}\right)+c_3^s\left(\overline{E_t^{s}}+\overline{E_{t+1}^{s}}\right) \tag{3.18}$$

From Equation 3.18, three parameters of a shrimp fishery $r_s=\frac{2\left(1-c_2^s\right)}{\left(1+c_2^s\right)}$, $q_s=-c_3^s\left(2+r_s\right)$ and $K_s=\frac{e^{\frac{c_1^s\left(2+r_s\right)}{2r_s}}}{q_s}$ are estimated.

The CY&P (1992) model is estimated for a fish fishery:

$$\ln\left(\overline{U_{t+1}^{f}}\right)=\left(\frac{2r_f}{2+r_f}\right)\ln\left(q_f K_f\right)+\left(\frac{2-r_f}{2+r_f}\right)\ln\left(\overline{U_t^{f}}\right)-\left(\frac{q_f}{2+r_f}\right)\left(\overline{E_t^{f}}+\overline{E_{t+1}^{f}}\right) \tag{3.19}$$

and the OLS technique for the fish fishery is applied to the following equation:

$$\ln\left(\overline{U_{t+1}^{f}}\right)=c_1^f+c_2^f\ln\left(\overline{U_t^{f}}\right)+c_3^f\left(\overline{E_t^{f}}+\overline{E_{t+1}^{f}}\right) \tag{3.20}$$

From Equation 3.20, three parameters of a fish fishery $r_f=\frac{2\left(1-c_2^f\right)}{\left(1+c_2^f\right)}$, $q_f=-c_3^f\left(2+r_f\right)$ and $K_f=\frac{e^{\frac{c_1^f\left(2+r_f\right)}{2r_f}}}{q_f}$ are estimated.

Using the estimated parameters r, q and K the biomass dynamic models for both shrimp and fish fisheries are estimated.

The OLS results of CY&P models for both shrimp and fish models are obtained from the solver macro of Microsoft Office EXCEL 2007 software, which are shown in Table 3.3.

Table 3.3 **Results: CY & P models**

A. Shrimp fishery:

$$\ln\left(\overline{U^s_{t+1}}\right) = 0.341 + 0.123\ln\left(\overline{U^s_t}\right) - 7.5\times10^{-4}\left(\overline{E^s_t} + \overline{E^s_{t+1}}\right)$$

$$\text{se}: \quad (0.377) + (0.273) \qquad (0.00003)$$

Multiple R : 0.74

R^2 : 0.54

Adjusted R^2 : 0.46

DW : 2.14

B. Fish fishery

$$\ln\left(\overline{U^f_{t+1}}\right) = 1.406 + 0.326\ln\left(\overline{U^f_t}\right) - 3.9\times10^{-5}\left(\overline{E^f_t} + \overline{E^f_{t+1}}\right)$$

$$\text{se}: \quad (0.587) + (0.279) \qquad (0.00001)$$

Multiple R : 0.97

R^2 : 0.95

Adjusted R^2 : 0.94

DW : 1.76

Note: 'se' denotes standard error
Source: Author's calculation

All coefficients in CY&P models for both shrimp and fish have the expected signs. But, the standard errors on the model coefficient are very high, indicating the problems of multicollinearity. Multicollinearity exists due to the classic 'one way-trip' which is a common problem when estimating surplus production models comparing CPUE series (Figure 3.4) with the effort series (Figure 3.3). The Durbin-Watson test for autocorrelation is applied for both models. The Durbin-Watson test for shrimp model (2.14) and fish model (1.76) show similar results to the CY&P model (2.92) and the Fox model (1.80) applied by Clarke et al (1992).

Both shrimp and fish models show a good fit to the time series data. The Multiple R, R^2 and Adjusted R^2 of shrimp model is smaller than those of the fish model. In both cases, the R^2 and Adjusted R^2 also show similar results of the different models applied by Clarke et al (1992).

Using the estimated parameters r, q and K from Table 3.3 both shrimp and fish biomass, catch and effort at the equilibrium (steady-state) and at the MSY are estimated, shown in Table 3.4.

Table 3.4 **Biomass, catch and effort**

	Equilibrium	MSY
A. Shrimp fishery		
Biomass:	$B^s_{Steady-state} = K^s e^{-\frac{q^s E^s}{r^s}}$	$B^s_{MSY} = \frac{K^s}{2.72}$
Catch:	$C^s_{Steady-state} = q^s E^s K^s e^{-\frac{q^s E^s}{r^s}}$	$C^s_{MSY} = \frac{r^s K^s}{2.72}$
Effort:	$E^s_{Steady-state} = \frac{r^s}{q^s} \ln\left(\frac{K^s}{B^s}\right)$	$E^s_{MSY} = \frac{r^s}{q^s}$
B. Fish fishery		
Biomass:	$B^f_{Steady-state} = K^f e^{-\frac{q^f E^f}{r^f}}$	$B^f_{MSY} = \frac{K^f}{2.72}$
Catch:	$C^f_{Steady-state} = q^f E^f K^f e^{-\frac{q^f E^f}{r^f}}$	$C^f_{MSY} = \frac{r^f K^f}{2.72}$
Effort:	$E^f_{Steady-state} = \frac{r^f}{q^f} \ln\left(\frac{K^f}{B^f}\right)$	$E^f_{MSY} = \frac{r^f}{q^f}$

Source: Author's calculation.

The derivation of biomass, catch and effort at the equilibrium (steady-state) and at the MSY are shown in Appendix C and D. The current biomass for both shrimp and fish is calculated using $B^s_{current} = \frac{U^s}{q^s}$ and $B^f_{current} = \frac{U^f}{q^f}$, respectively.

Estimated results show that between 1992 and 2007, average abundance of shrimp biomass per year (1594 tonnes) is below the biomass at MSY level (2034 tonnes). The results also show that average fishing pressure per year (7457 fishing days) is larger than the fishing effort at the MSY (5857 fishing days) level. The average catch per year (3148 tonnes) is a little lower than the catch at MSY (3178 tonnes). The result of the average abundance of shrimp biomass being below the biomass at MSY shows that the shrimp stock of the industrial marine fisherise is over-exploited, which is consistent with Department of Fisheries' report (2007) and indicates urgent need for management actions for shrimp fisheries. It is confirmed from the results that the fall in CPUE over time in Figure 3.4 of the industrial marine shrimp fishery is due to the fall in stock size. Results also show that too much effort is used to maintain high catch in the shrimp fishery which leads to the possible extinction of the shrimp fishery as the current effort (7457 fishing days) is higher than the effort at MSY level (5857 fishing days). So, there is a need for a reduction of effort in shrimp fishery. The estimated parameters; current abundance of biomass; biomass, catch and effort at MSY; biomass, catch and effort at steady-state of the shrimp fishery are shown in Table 3.5.

Table 3.5 **Values of estimated parameters, biomass, catch and effort of shrimp**

	Description	Current	MSY	Steady-state equilibrium
B_s	Biomass (tonnes)	1594	2034	1549
C_s	Catch (tonnes)	3148	3178	3081
E_s	Effort (fishing days)	7457	5857	7291
r_s	Intrinsic growth rate	1.562462		
q_s	Catchability in fishing days	0.000267		
K_s	Maximum biomass (tonnes)	5533		

Source: Author's calculation

The estimated results between 1992 and 2007 show that the average abundance of fish biomass per year (51556 tonnes) is above the biomass at MSY level (25156 tonnes). The results also show that average fishing pressure per year (3447 fishing days) is smaller than the fishing effort at the MSY (8642 fishing days) level. The average catch per year (16730 tonnes) is also lower than the catch at MSY (25574 tonnes). The result of the average abundance of fish biomass being above the biomass at MSY shows that the fish stock of the industrial marine fisheries is under-exploited. Hence, it is confirmed that the fall in CPUE over time in Figure 3.4 of the industrial marine fish fishery is not due to the fall in stock size. It may be due to the knowledge and information on the availability of the sizes of different fish stocks and may be partly due to the lack of technological developments for harvesting the new resources as mentioned in the DoF's Report (2007). So, it is important to increase the knowledge and information on the availability of the sizes of different fish stocks and to improve technological development of harvesting the marine fish resource. The estimated parameters; current abundance of biomass; biomass, catch and effort at MSY; biomass, catch and effort at steady-state of the fish fishery are shown in Table 3.6.

Table 3.6 **Values of estimated parameters, biomass, catch and effort of fish**

	Description	Current	MSY	Steady-state equilibrium
B_f	Biomass (tonnes)	51556	25156	45918
C_f	Catch (tonnes)	16730	25574	18620
E_f	Effort (fishing days)	3447	8642	2446
r_f	Intrinsic growth rate	1.016615		
q_f	Catchability in fishing days	0.000118		
K_f	Maximum biomass (tonnes)	68425		

Source: Author's calculation

The abundance of biomass and actual catch in Table 3.5 and 3.6 show that to maintain steady-state biomass for both shrimp (1594 tonnes) and fish (45918 tonnes), in both shrimp and fish fisheries, steady-state catch should be 3081 tonnes and 18620 tonnes, respectively (in both cases, average current effort levels between 1992 and 2007 are used). The actual average catch of both shrimp (3148 tonnes) and fish (16730 tonnes) shows that both fisheries are not in steady-state equilibrium. It also indicates that the growth of both shrimp and fish are also not at adequate levels. As correspondence to each biomass level, a certain catch rate balances the growth rate of the resource and thus maintains steady-state equilibrium, the situation signals that both shrimp and fish are caught in small sizes. This may be due to the fishing pattern or technology (such as mesh size). Currently in the industrial marine fisheries, 45mm and 60mm mesh size of the net at the cod-end are used for a shrimp fishery and a fish fishery, respectively. To maintain steady-state equilibrium by maintaining adequate growth rate of both shrimp and fish, fishing patterns may also need to be modified.

3.5 Conclusion

This study is the first of its kind in terms of its study area and use of models to calculate the biological parameters. This study goes beyond 40 metres depth within the EEZ of Bangladesh to estimate biological reference points and to measure the current status of the industrial marine fisheries. This study uses CY&P (1992) models to calculate the biological parameters. Using two separate CY&P models, this study develops biomass dynamic models: dynamic versions of surplus production models for the shrimp fishery and the fish fishery of the industrial marine fisheries of Bangladesh. A time series data over the period from 1992 to 2007 is used in this study. Biological reference points are estimated in terms of Maximum Sustainable Yield (MSY). To find out the biological reference points, the OLS technique is applied. Using the OLS results intrinsic growth rate, catchability coefficient and maximum biomass are estimated, which gives the abundance of biomass, biomass at the MSY and biomass at the steady-state for both shrimp and fishery. The steady-state catch and effort for both shrimp and fish fishery are also estimated.

The estimated results show that the average abundance of shrimp biomass is below the biomass at MSY. Results indicate that the shrimp stocks of the industrial marine fisheries are over-exploited and the fall in CPUE over time of the industrial marine shrimp fishery is due to the fall in stock size. Results also show that too much effort is used to maintain high catch in the shrimp fishery, which will lead to the possible extinction of the shrimp fishery. So, there is a need for a reduction of effort in shrimp fishery and management actions are urgently needed for shrimp fishery to increase the stock size. On the other hand, the result of the average abundance of fish biomass is above the biomass at MSY and the current effort of fish fishery is much smaller than the critical level of effort at MSY level. The average abundance of fish biomass indicates that the fish stocks of the industrial marine fisheries are under-exploited and the fall in CPUE over time of the industrial marine fish fishery doesn't show that it is due to the fall in stock size. It may be due to the knowledge and information on the availability of the sizes of different fish stocks and may be partly due to lack of technological developments for harvesting the new resources. So for fish fishery, management action is needed to increase the knowledge and information on the availability of the sizes of different fish stocks, and to improve technological development of harvesting the marine fish resource. Both shrimp and fish fisheries results are consistent with the results in Chapter 2, which shows an outward shift of production of all vessels in both shrimp and fish fleets over the period indicating that too much effort is being used and signalling a possible decline in catch for both high-valued and low-valued catch. Results of this study also show that high-valued shrimp stock is small, as much literature shows a decline in high-valued stock and the low-valued fish stock is large due to an inadequate use of fishing technology as reported from the technical progress in Chapter 2.

The steady-state equilibrium results show that both shrimp and fish fisheries are not in steady-state equilibrium. It also indicates that the growth rate of both shrimp and fish stocks are also not in the adequate level. The situation signals that both shrimp and fish are caught in small sizes. This may be due to the fishing pattern and technology (such as mesh size). To maintain steady-state equilibrium and adequate growth rate of both shrimp and fish stocks, fishing patterns may also need to be modified. Overall, the results of this study indicate that the current management system (such as input control by licensing for both shrimp and fish fisheries and season closure for shrimp fishery) is not enough to increase the level of high-valued shrimp stocks and to increase the catch level of the low-valued stocks. Results show a need for an alternative management strategy for industrial marine fisheries in Bangladesh.

Appendix C

Derivation of the equilibrium solution

In the absence of harvest, biological growth of biomass:

$$\frac{dB}{dt} = rB\ln\left(\frac{K}{B}\right) \tag{C1}$$

Harvest function:

$$C = qEB \tag{C2}$$

With harvest, biological growth of biomass:

$$\frac{dB}{dt} = rB\ln\left(\frac{K}{B}\right) - C \tag{C3}$$

At steady-state, $\frac{dB}{dt} = 0$

$$\Rightarrow rB\ln\left(\frac{K}{B}\right) = C \tag{C4}$$

From Equation C4, equilibrium effort and biomass are obtained:

$$E_{eq} = \frac{r}{q}\ln\left(\frac{K}{B}\right) \tag{C5}$$

$$B_{eq} = Ke^{-\frac{qE}{r}} \tag{C6}$$

Substituting $E_{eq} = \frac{r}{q}\ln\left(\frac{K}{B}\right)$ and $B_{eq} = Ke^{-\frac{qE}{r}}$ into Equation C2, the equilibrium harvest is obtained:

$$C_{eq} = qEKe^{-\frac{qE}{r}} \tag{C7}$$

So, the biomass, effort and harvest at the equilibrium are:

Biomass: $B_{eq} = Ke^{-\frac{qE}{r}}$

Effort: $E_{eq} = \frac{r}{q}\ln\left(\frac{K}{B}\right)$

Harvest: $C_{eq} = qEKe^{-\frac{qE}{r}}$

Appendix D

Derivation of MSY

Taking first derivative of harvest in Equation C7 (Appendix C) with respect to effort,

$$\frac{dC}{dE} = qKe^{-\frac{qE}{r}}\left[1 - \frac{qE}{r}\right] \tag{D1}$$

At maximum, $\frac{dC}{dE} = 0$

$$\Rightarrow qKe^{-\frac{qE}{r}} = qKe^{-\frac{qE}{r}}\frac{qE}{r} \tag{D2}$$

Solving Equation D2, the effort at MSY is obtained:

$$E_{MSY} = \frac{r}{q} \tag{D3}$$

Substituting $E_{MSY} = \frac{r}{q}$ into Equation C6 (Appendix C), the biomass at MSY is obtained:

$$B_{MSY} = \frac{K}{2.72} \tag{D4}$$

Substituting $E_{MSY} = \frac{r}{q}$ and $B_{MSY} = \frac{K}{2.72}$ into Equation C2 (Appendix C), the harvest at MSY is obtained:

$$C_{MSY} = \frac{rK}{2.72} \tag{D5}$$

So, the biomass, effort and harvest at the MSY are:

Biomass: $$B_{MSY} = \frac{K}{2.72}$$

Effort: $$E_{MSY} = \frac{r}{q}$$

Harvest: $$C_{MSY} = \frac{rK}{2.72}$$

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Chapter 4

Economic efficiency of the industrial marine fisheries of Bangladesh: a bio-economic analysis

4.1 Introduction

Overcapacity, overharvesting, habitat damage and poor economic returns are considered main challenges to many of the world's fisheries (Hilborn et al 2003). In an open access resource issues such as lack of property rights over the fish; effective management of the resource; cooperation among harvesters and free entry into a fishery by outsiders increase negative externalities in fisheries, known as tragedy of the commons. To prevent negative externalities, many fisheries in the world have taken some policy actions, such as restricting access to fishing grounds, limiting Total Allowable Catch (TAC) by fishing fleets and so on. Despite these policy actions there have been several stock collapses occurred, such as northern cod fishery of Newfoundland and Labrador (Grafton et al 2006). Many economists argue that the most extreme example of management mistakes are stock collapses, which is caused by a lack of appropriate incentives and institutions that encourage fishers to behave in a sustainable way.

To maintain sustainable stocks, the traditional approach has been input and output control measures, such as restricting the number of vessels, use of gear, number of fishing days, the length of closed seasons, the size of the catch limit, etc.. Studies show that input control increases substitution from regulated to unregulated inputs (Wilen 1979) and results in effort-creep, and excessive and wasteful competition (Kompas et al. 2009) in the fishery. In the long run, these measures cannot prevent economic overfishing, and fail to maximize economic profit and hence economic efficiency in the fishery. Overall, a laissez-faire approach to fisheries doesn't work to address a tragedy of commons and other failures associated with open access fisheries (Grafton et al 2006). So, an economic perspective of fisheries management is necessary, which shows marine resources should be managed sustainably so that they can contribute to and provide net benefit for the nation as a whole. Thus, an economically viable fishery can be an ecologically sustainable fishery.

To achieve maximum economic efficiency from a fishery correct and effective management targets are important. Efficient management of a fishery protects stocks, guarantees sustainability and assures correct allocation of resources in a way that maximizes the returns from fishing (Grafton et al 2006; Kompas 2005). A benchmark to compare current economic performances in fishery with potential economic performances is explained by Maximum Economic Yield (MEY), which depends on a combination of biological and economic factors (Grafton et al 2006). The combination of biological and economic factors gives a simultaneous biological and economic equilibrium in a fishery, which is commonly known as bio-economic[52] equilibrium.

A good deal of research on bio-economic modeling has been done on both single-species fisheries[53] and multi-species and/or multi-fleet fisheries[54]. A limited number of studies (Kar & Chakraborty 2011; Khan 2007; Khan & Karim n.d.) are done on marine shrimp fishery of Bangladesh. Based on area, marine fisheries of Bangladesh consist of two fisheries: artisanal[55] fisheries and industrial[56] fisheries and the characteristics of these two fisheries are different. The study done by Kar & Chakraborty (2011) doesn't highlight the area of study, that is, whether the study deals with artisanal shrimp or industrial shrimp or marine shrimp fishery as a whole. The other two studies (Khan 2007; Khan & Karim n.d.) have been done on shrimp trawl fishery, that is, the area of study of these two studies is industrial shrimp. Khan (2007) calculates optimal stock, harvest and effort level in discrete time frames and shows that the fishery is not managed and utilized optimally. Khan & Karim (n.d.) calculate optimal fishing effort and harvest level using both static and dynamic models and shows that shrimp capture fishery is exploited in an unsustainable manner. Kar & Chakraborty (2011) also use both static and dynamic frameworks to investigate the optimal utilization of shrimp resources, sustainability of stock and resource rent earned. The previous studies on

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[52] Bio-economic models explain functional relationships between specific characteristics of the natural resource base, (for example, a fishery resource), and the human activities to make use of such a natural resource (FAO 1998).

[53] Abaunza et al 2003; Anderson 2002; Armstrong & Skonhoft 2006; Bene et al 2001; Bjorndal et al 2004; Bolmo et al 1978; Chaudhuri & Johnson 1990; Christensen & Vestergaard 1993; Clarke et al 1992; Conard 1989; Eggert & Ulmestrand 2000; Grant et al 1981; Holland 2000; Ibaibarriaga et al 2008; Kar & Matsuda 2008; Khan 2007; Mackinson et al 1997; McConnell & Sutinen 1979; Rettig 1987.

[54] Agar & Sutinen 2004; Bhat & Bhatta 2006; Chaudhuri 1986; Chaudhuri 1988; Crutchfield 1983; Eggert 1998; Fredou et al 2009; Kompas & Che 2006; Kompas et al 2010; Lleonart et al 2003; Matsuda & Abrams 2006; Pelletier et al 2009; Pradhan & Chaudhuri 1999; Ruttan et al 2000; Ulrich et al 2002; Ward 1994.

[55] The *artisanal fisheries are* small-scale onshore fisheries and fishing occurs up to 40 metres depth with mechanized and non mechanized boats.

[56] The *industrial fisheries are* large-scale offshore fishery and fishing occurs beyond 40 metres depth within the EEZ of Bangladesh with industrial vessels.

marine shrimp of Bangladesh (Kar & Chakraborty 2011; Khan 2007; Khan & Karim n.d.) use the logistic growth model. The biological parameters and price of shrimp of these studies are used from secondary sources.

The objective of this study is to measure the economic performance of the industrial marine fisheries of Bangladesh. This is the first study of its kind that covers both shrimp and fish of the industrial marine fisheries of Bangladesh. The industrial marine fisheries of Bangladesh are open access fisheries and the industrial fishing fleets of Bangladesh have been expanding over time (Marine Fisheries Department (MFD) 2009). The management system of industrial marine fisheries of Bangladesh is mainly designed to control the effort level in order to prevent stock depletion. The management system is licensing vessels and the license fees are based on Gross Tonnage (GT) of the vessels. Commercially important fisheries resources: shrimp[57] and fish[58] are harvested by the industrial fishing vessels. Based on target species, industrial fishing vessels are divided into two broad categories: shrimp[59] fleet and fish[60] fleet. Hence, this study develops two single-species and single-fleet models separately for both shrimp and fish fisheries. Current and potential economic performance of both shrimp and fish fisheries in this study are measured using three different bio-economic models: a bio-economic model for open access fishery, a static profit maximization problem and a dynamic present value-maximization problem in continuous time. A harvest function given by Schaefer (1954) and Munro (1981, 1982) is used in this study. For both shrimp and fish of the industrial marine fisheries of Bangladesh, this is the first kind of study that uses the Gompertz curve (Richards 1959) in the biological growth models; biological parameters are derived following CY&P (1992) models. Price of harvest and cost per unit effort in this study are estimated separately. The equilibrium biomass, effort and profit at bio-economic equilibrium of open access fishery, at static MEY and dynamic MEY are compared with the Maximum Sustainable Yield (MSY). Sensitivity to changes in price

[57] The key commercial marine shrimp species harvested by the industrial vessels are tiger shrimp (*Penaeus monodon*) and brown shrimp (*Metapenaeus monodon*). *Penaeus monodon* (tiger shrimp) is the most valuable and hence the targeted species. But the highest (almost two thirds of the total) contribution to the total catch is from *Metapenaeus monodon* (brown shrimp) (MFD 2009).

[58] More than ninety fish species are commercially important. These fall under the common group. The major commercial fin fish species exploited by the industrial vessels are pomfret (*Pampus argenteus*), goatfish (*Upenuus sulphureus*), bream (*N. japonicas*), lizard fish (*Saurida tumbil*), grunter (*Popmadasys hasta*), red snapper (*Lutjanus johnii*) and carangid (*Arioma indica*) (MFD 2009).

[59] Vessels in the shrimp fleet are double-rigged vessels, fitted with two side beams from which two shrimp-trawl nets are simultaneously operated. A standard shrimp vessel is made of a steel hull and mesh size of the net at the cod-end is 45mm.

[60] Vessels in fish fleet are stern vessels with a single-rigged trawl-net operated behind the vessels. These vessels generally have both wooden and steel hulls and the mesh size of the net at the cod-end is 60mm.

of harvest, changes in cost per unit effort and changes in social discount rate on biomass are also examined. The study shows that excessive use of efforts makes both shrimp and fish fisheries economically inefficient in the form of low stock biomass and profit. Thus both shrimp and fish fishery show that both fisheries are neither, economically viable nor, ecologically sustainable.

The remainder of this chapter is divided into five sections. Section 4.2 focuses on the theoretical framework followed by models for the industrial marine fisheries of Bangladesh in Section 4.3. Section 4.4 describes the data and variables. Section 4.5 presents results, while Section 4.6 concludes the chapter.

4.2 Theoretical framework

A benchmark to compare current economic performances in fisheries with potential economic performances is explained by Maximum Economic Yield (MEY). MEY depends on a combination of biological and economic factors (Grafton et al 2006). The combination of biological and economic factors gives a simultaneous biological and economic equilibrium in a fishery, which is commonly known as bio-economic equilibrium (FAO 1998). Bio-economic modeling in fisheries helps to describe the management of fisheries resources and to integrate the economic and biological influences in determining appropriate levels of stock and harvest (Knowler 2002).

Bio-economic modeling can be done based on stochastic and deterministic conditions. The optimal policy under stochastic conditions is qualitatively different from the optimal policy under deterministic conditions (Anderson & Sutinen 1984) and on average deterministic policies are reasonably good substitutes for stochastic policies (Lewis 1981; Smith 1977). Bio-economic modeling can also be done using static (time-independent) and dynamic (time-dependent) analysis. Since the 1970s, a major development and decisive shift away from static to dynamic analysis has placed economists in a position to effectively analyze fisheries management programs (Clark et al. 1985). A dynamic modeling approach for the resource performs estimations and predictions of the bio-economic impact derived from different management strategies (FAO 2002). Recent literature shows that the dynamic bio-economic model has started to become accepted as an important and implementable target in fisheries management (eg., Grafton et al. 2010). However, both static and dynamic approaches are used in this study to measure the Maximum Economic Yield (MEY) along with the open access bio-economic equilibrium for both shrimp and fish fisheries.

Bio-economic models are used for both single-species/single-fleet and multi-species/multi-fleet fisheries. Different types of bio-economics models for single-species/single-fleet are used in the literature. These include static and dynamic versions of the Schaefer model (Gordon 1953, 1954); a distributed-delay fleet dynamics model based on Smith's model (1969); and yield-mortality models and age-structured dynamic models (Seijo & Defeo 1994) and so on. The majority of multi-species/multi-fleet models are extension of single-species/single-fleet models (FAO 1998). Bio-economic models for multi-species/multi-fleet fisheries depend on mainly three interactions: biological, technical and economic. Biological interaction describes the interaction between and within fish stocks and this interaction is caused by predation and food competition. Studies on biological interactions have been conducted by many authors. Most popular models on biological interactions are the 'Multi-species VPA'[61]. The classical predator-prey models are based on logistic models and Lotka-Volterra models (Lotka 1925; Volterra 1926) and these models are used in some studies (Goh 1976; Hastings 1978). Food web modeling is also found in a few studies, such as Walters & Martell (2004). Simultaneous harvest of groups of species is involved with technical interactions. Models where two ecologically independent stocks are jointly harvested with the same gear are based on the Gordon-Schaefer model (Gordon 1953, 1954) and models where two ecologically independent stocks are harvested independently and competition exists between two stocks are based on the Gause model (Gause 1935). Technical interaction models, such as those used in Brown et al (1976) and Ralston & Polovina (1982) can be appropriate both for interacting and non-interacting species groups (Hollowed et al 2000).

Economic interaction describes the competition between fleets. The more one fleet catches of the limited resource the less will be left for its competitors (FAO 1998). The economic interactions capture price and value of harvest and these models are also known as the prediction models. The first prediction models were developed by Thompson & Bell (1934), where economic interaction of several fleets was introduced to the age-based models. Economic interaction is also described by the Beverton & Holt

[61] For example, Helgason & Gislason 1979; Gislason & Helgason 1985; Pope 1979; International Council for the Exploration of the Sea (ICES) 1984, 1986, 1987; Gislason & Sparre 1987.

models (1957). Market interaction also played an important role in multi-species/multi-fleet fisheries and this interaction is considered when the quantity of one species supplied affects the market price of another species (Flaaten 1998). This study uses single-species and single-fleet models for the bio-economic analysis of the industrial marine shrimp and fish fisheries of Bangladesh.

The bio-economic model consists of two components: a biological growth model and economic model (Perman et al 2011). The biological growth model describes the natural growth process of the fishery, while the economic model describes the economic behavior of the vessel owners.

4.2.1 Biological growth model

In the absence of harvest, the rate of change of biomass depends on the current biomass, which is known as the biological growth model and can be expressed as:

$$\frac{dB}{dt} = F(B) \tag{4.1}$$

In the Equation 4.1, B is the biomass; t is the year; $\frac{dB}{dt}$ is the growth rate of biomass and $F(B)$ is the growth function of biomass. According to Clarke et al (1992), five different models for $F(B)$ are used in different studies to describe the biological production relationship. All these models are mentioned in Chapter 3 (see page 100). These models are different in terms of different production relationships, such as parabolic/logistic relation between yield and effort in the Schaefer model (1957) and the Schnute model (1977); Gompertz curve (Richards 1959) in the Fox model (1970) and the CY&P model (1992); logarithmic relation between yield and effort in the Threshold model by Sathiendrakumar & Tisdell (1987). A parabolic/logistic curve for Bangladesh marine shrimp fishery is used in Kar & Chakraborty (2011); Khan (2007) and Khan & Karim (n.d.). Following the CY&P model (1992), this study uses Gompertz curve (Richards 1959) in the biological growth model.

A steady-state biological equilibrium occurs when the net growth of biomass is exactly equal to the rate of harvest and the fishery can then continue indefinitely in this position of sustained harvesting of fish. Thus, the biological equilibrium can be written as:

$$F(B) = h(E, B) \tag{4.2}$$

4.2.2 Economic model

The economic model consists of harvest function, cost function, revenue/benefit function and profit function, and can be expressed as:

$$\left.\begin{aligned} h &= h(E, B) \\ TC &= C(E) \\ TR &= B(h) \\ \pi &= TR - TC \end{aligned}\right\} \tag{4.3}$$

In Equation 4.3, h is the harvest and the size of harvest normally depends on many factors. In this case, harvest depends on mainly two factors. The first factor is effort E, which can be measured either in terms of number of vessels or number of fishing days. The second factor is biomass B. For any given level of effort, the larger the biomass the greater the harvest. Depending on different assumptions, different harvest functions are used in different studies. The foundation of harvest functions for most dynamic fishery models is the Scheafer or the biomass and effort Cobb-Douglas harvest function (Morey 1986). Mainly, two types of harvest functions are used in the literature. Of these, the harvest functions depends on the amount of fishing effort and biomass given by Schaefer (1954) and Munro (1981, 1982) is considered as a good approximation to the actual relationship. The other harvest function is the Beverton and Holt (1954, 1957) harvest function, which depends on recruitment, growth of stock and fishing mortality. Harvest functions given by Scheafer (1954) and Munro (1981 and 1982) are used in this study.

With harvest, the growth rate of biomass in Equation 4.1 depends on the current biomass less the quantity of harvest, which can be expressed as:

$$\frac{dB}{dt} = F(B) - h(E,B) \tag{4.4}$$

The total cost of harvest TC in Equation 4.3 depends on amount of effort E. In a commercial fishery, the gross benefit is the total revenue of the fishery (Perman et al 2011) and the total revenue TR depends on amount of harvest h. The profit function π in Equation 4.3 shows that the profit is the difference between total revenue (TR) from harvest and total cost (TC) of harvest.

Gordon (1954) shows[62] that in the absence of entry limitations, total revenues and costs eventually equilibrate and all resource rent/profit will be dissipated. Thus, in an open access fishery the economic equilibrium occurs when profit is zero, that is, the total revenue from harvest is exactly equal to the total cost of harvest. Hence, the economic equilibrium of the open access fishery can be expressed as:

$$\pi = 0 \Rightarrow TR = TC \tag{4.5}$$

The equilibrium condition in Equation 4.5 shows at the steady-state, $\frac{dE}{dt} = 0$ and effort is constant. Because, in an open access fishery, the entry and exit of vessels (fishing effort) depends on profit, which is determined as:

$$\frac{dE}{dt} = \delta\pi \tag{4.6}$$

With positive profit ($\pi > 0$), vessels will enter into the fishery and with negative profit ($\pi < 0$), vessels will leave the fishery, which can be written as:

$$\left.\dot{E} = \frac{dE}{dt} = \delta\pi\right\} \Rightarrow \begin{cases} \pi > 0 \Rightarrow entry \\ \pi < 0 \Rightarrow exit \end{cases} \tag{4.7}$$

[62] Gordon (1954) analysis assumed that the fleet was homogeneous and the average cost equal to the marginal cost, and also includes a normal return to capital.

The magnitude of entry into and exit from a fishery depends on the positive parameter δ that indicates the responsiveness of the fishing industry size to industry profitability (Perman et al 2011).

By solving biological equilibrium presented in Equation 4.2 and economic equilibrium in Equation 4.5, the steady-state biomass, effort and amount of harvest for an open access fishery are obtained.

MEY is the equilibrium level, where the economic rent/profit is maximized. A static MEY is obtained using the following profit maximization problem:

$$\text{Max } \pi(E) = TR(E) - TC(E) \tag{4.8}$$

The first order necessary condition for maximum profit is $\frac{\partial \pi}{\partial E} = 0$, which shows that at maximum profit, the marginal revenue from harvest is equal to the marginal cost of harvest:

$$\frac{dTR(E)}{dE} = \frac{dTC(E)}{dE} \tag{4.9}$$

Solving the biological equilibrium presented in Equation 4.2 and the economic equilibrium in Equation 4.9, the steady-state biomass, effort and amount of harvest for static MEY are obtained.

A dynamic MEY is obtained using present value-maximizing models, which considers the value of time (Clark 1989) and takes account of the process of adjustment by which an optimal stock size is attained (Knowler 2002). This model requires the use of optimal control theory where harvest (h), fishing effort (E) and biomass (B) are expressed as functions of time. The fisheries resource manager's problem is to maximize the present value of exploiting the resources and the general form of dynamic problem in continuous time is expressed as:

$$\text{Max } NB = \int_0^{\infty} e^{-\rho t}\pi(t).dt \quad \text{subject to:} \quad \begin{cases} \dfrac{dB}{dt} = F[B(t)] - h(t) \\ B(0) = B_0 \\ 0 \le h(t) \le h^{\max} \\ or \\ 0 \le E(t) \le E^{\max} \end{cases} \tag{4.10}$$

In Equation 4.10, NB is the net benefit; ρ is the instantaneous annual discount rate or the social discount rate of the resource; t is the year and $\pi(t)$ is the profit function. The constraint the net growth rate of biomass, $\frac{dB}{dt} = F[B(t)] - h(t)$ is the state equation; B_0 is the initial value of the biomass; $h(t)$ is the harvest and $E(t)$ is effort. It is largely a matter of convenience whether harvest or effort is used as constraint (Perman et al 2011). As the industrial marine fisheries of Bangladesh is an effort-controlled fishery, this study uses effort as the control variable for both shrimp and fish fisheries.

The current value Hamiltonian for the problem is:

$$H^c(E,B) = \pi(t) + \mu[F\{B(t)\} - h(t)] \tag{4.11}$$

The necessary conditions or, the maximum principles for optimal solution are:

$$\left.\begin{aligned} &(i)\frac{\partial H^c}{\partial E} = 0 \\ &(ii)\frac{\partial H^c}{\partial \mu} = \frac{dB}{dt} \\ &(iii)\dot{\mu} - \rho\mu = -\frac{\partial H^c}{\partial B} \end{aligned}\right\} \tag{4.12}$$

At steady-state, $\dot{B} = \dot{\mu} = 0$. The optimal biomass, optimal effort and optimal harvest for a dynamic MEY are obtained by solving maximum principles. Depending on ρ, there may be one, several or no solutions (Clark 1973).

4.3 Models

All vessels within the fleets in the industrial marine fisheries of Bangladesh are considered as homogeneous vessels in terms of gear. Both shrimp and fish fleets are independent in their targeted catch. According to the data of the Marine Fisheries Department (MFD) of Bangladesh between 2001 and 2007, the major amount of total targeted catches of shrimp comes from shrimp fleet (99.09 percent) and the amount of total targeted catches of fish comes from fish fleet (71.93 percent). The management conditions allow both shrimp and fish fleets to catch 30 percent of bycatch, but due to the use of different gear and mesh sizes the average bycatch of both fleets, in fact, is very low. So, the bycatch of both shrimp fleet (28.73 percent fish) and fish fleet (0.91 percent shrimp) are ignored in this study and the targeted resources (shrimp and fish) are considered as homogeneous biomasses. Hence, both shrimp and fish fisheries in this study are considered as two different independent single-species fisheries. Hence, this study uses two separate single-species and single-fleet models for a shrimp fishery and a fish fishery. These models are developed under two assumptions. First, the models are considered as equilibrium models. Second, state of nature has no uncertainty.

4.3.1 Biological growth model

Using a Gompertz curve (Richards 1959) the biological growth models for both shrimp (s) and fish (f) fisheries of industrial marine fisheries of Bangladesh are measured separately, which are expressed as:

$$\frac{dB^s}{dt} = F^s\left(B^s\right) = r^s B^s \ln\left(\frac{K^s}{B^s}\right) \tag{4.13}$$

$$\frac{dB^f}{dt} = F^f\left(B^f\right) = r^f B^f \ln\left(\frac{K^f}{B^f}\right) \tag{4.14}$$

Equation 4.13 and 4.14 show that for both shrimp (s) and fish (f) fisheries of industrial marine fisheries of Bangladesh, the growth rate of the biomass $\frac{dB}{dt}$ and the shape of the growth $F(B)$ relies on the two biological parameters r and K, where r is the intrinsic growth rate and K is the maximum stock level or virgin biomass.

4.3.2 Economic model

The two economic models for both shrimp(s) and fish(f) fisheries of industrial marine fisheries of Bangladesh consist of four functions: harvest function, total cost function, total revenue function and profit function. The economic models of both shrimp(s) and fish(f) fisheries are expressed as:

$$\left.\begin{aligned} h^s &= h^s(E^s, B^s) \Rightarrow h^s = q^s B^s E^s \\ TC^s &= C^s(E^s) \Rightarrow w^s E^s \\ TR^s &= B^s(h^s) \Rightarrow p^s h^s \Rightarrow p^s q^s B^s E^s \\ \pi^s &= TR^s - TC^s \Rightarrow (p^s q^s B^s - w^s)E^s \end{aligned}\right\} \quad (4.15)$$

$$\left.\begin{aligned} h^f &= h^f(E^f, B^f) \Rightarrow h^f = q^f B^f E^f \\ TC^f &= C^f(E^f) \Rightarrow w^f E^f \\ TR^f &= B^f(h^f) \Rightarrow p^f h^f \Rightarrow p^f q^f B^f E^f \\ \pi^f &= TR^f - TC^f \Rightarrow (p^f q^f B^f - w^f)E^f \end{aligned}\right\} \quad (4.16)$$

Harvest function $h = qEB$ given by Scheafer (1954) and Munro (1981, 1982) is used in both Equation 4.15 and 4.16. The harvest function is $h = \sum_{i=1}^{n} c_i$, where $i = 1, 2, ..., n$ denotes number of vessels engaged in fishing and c denotes catch of vessel i. The harvest function relies on a simple multiplicative relationship between a constant catchability coefficient q, biomass B and total effort E. In the harvest function, $E = \sum_{i=1}^{n} e_i$ where $i = 1, 2, ..., n$ denotes number of vessels engaged in fishing and e denotes total effort given by vessel i.

With harvest, the growth rate of biomass of both shrimp(s) and fish(f) fisheries of the industrial marine fisheries of Bangladesh depend on the current biomass less the quantity of harvest and are expressed as:

$$\frac{dB^s}{dt} = F^s\left(B^s\right) - h^s\left(E^s, B^s\right) \Rightarrow r^s B^s \ln\left(\frac{K^s}{B^s}\right) - q^s B^s E^s \tag{4.17}$$

$$\frac{dB^f}{dt} = F^f\left(B^f\right) - h^f\left(E^f, B^f\right) \Rightarrow r^f B^f \ln\left(\frac{K^f}{B^f}\right) - q^f B^f E^f \tag{4.18}$$

Equation 4.17 and 4.18 depend on three parameters: the intrinsic growth r, the catchability coefficient q and the maximum stock level or virgin biomass K.

Under the assumption that all efforts given in both shrimp (s) and fish (f) harvesting of the industrial marine fisheries are targeted, the harvesting cost of this study is considered as a linear function of effort. Hence, Equation 4.15 and 4.16 show the harvesting cost is a linear function of effort E, that is, $TC = wE$ where w is the cost per unit of harvesting effort and considered as constant; and $E = \sum_{i=1}^{n} e_i$, $i = 1, 2, ..., n$ is the number of vessels engaged in fishing or total fishing days and e denotes total effort of harvest used by vessel i.

The total cost of harvest $TC(= w_1x_1 + w_2x_2 + w_3x_3)$ for both shrimp (s) and fish (f) fisheries of the industrial marine fisheries of Bangladesh is calculated separately using both fixed (total engine power x_1) input cost and variable input (total crew x_2 and total fishing days x_3) cost of both fleets. The input prices of total engine power, total crew and total fishing days w_1, w_2 and w_3 are derived using a cost minimization problem and calculated as, $w_1 = w_2 \frac{F_1}{F_2}$ and $w_3 = w_2 \frac{F_3}{F_2}$, where F_1, F_2 and F_3 are the marginal productivity of engine power, crew and fishing days, respectively.

Equation 4.15 and 4.16 show that the total revenue for both shrimp (s) and fish (f) fisheries of the industrial marine fisheries of Bangladesh is a simple multiplicative relationship between market price p and amount of harvest h. The amount of harvest used in this study is a sum of total catch by all vessels in the fleet. In an open access fishery, perfect competition exists and price is fixed for all vessels, i.e. $p = \overline{p}$ and the price of harvest is derived using long-run equilibrium condition where price is equal to average cost of harvest.

The profit function π for both shrimp(s) and fish(f) fisheries of industrial marine fisheries of Bangladesh in Equation 4.15 and 4.16 shows that the profit is the difference between total revenue from harvest TR and total cost of harvest TC .

4.3.3 Bio-economic equilibrium for open access fishery

The bio-economic equilibrium of both open access shrimp(s) and fish(f) fisheries satisfies the following conditions:

(i) $F(B) = h$ (biological equilibrium)

(ii) $TR = TC$ (economic equilibrium)

By solving these two conditions, equilibrium biomass, effort and harvest for both open access shrimp(s) and fish(f) fisheries are derived separately. The derivation of the solution is presented in Appendix E. The solution for equilibrium biomass$\left(B^{BE}\right)$, effort $\left(E^{BE}\right)$ and harvest $\left(h^{BE}\right)$ for both shrimp(s) and fish(f) fisheries at the open access bio-economic equilibrium are reported in the Table 4.1.

Table 4.1 **Solution: bio-economic equilibrium (BE) of open access fishery**

Shrimp fishery	Fish fishery
$B_s^{BE} = \dfrac{w^s}{p^s q^s}$	$B_f^{BE} = \dfrac{w^f}{p^f q^f}$
$E_s^{BE} = \dfrac{r^s}{q^s} \ln\left(\dfrac{p^s q^s K^s}{w^s}\right)$	$E_f^{BE} = \dfrac{r^f}{q^f} \ln\left(\dfrac{p^f q^f K^f}{w^f}\right)$
$h_s^{BE} = \dfrac{w^s r^s}{p^s q^s} \ln\left(\dfrac{p^s q^s K^s}{w^s}\right)$	$h_f^{BE} = \dfrac{w^f r^f}{p^f q^f} \ln\left(\dfrac{p^f q^f K^f}{w^f}\right)$

Source: Author’s calculation

Using the solution in Table 4.1, total revenue from harvest $\left(TR^{BE}\right)$, total cost of harvest $\left(TC^{BE}\right)$ and total profit $\left(\pi^{BE}\right)$ at the bio-economic equilibrium of both open access shrimp (s) and fish (f) fisheries are obtained.

4.3.4 Static MEY

The static MEY of both shrimp (s) and fish (f) fisheries satisfy the following conditions:

(iii) $F(B) = h$ (biological equilibrium)

(iv) $MR = MC$ (economic equilibrium)

Solving these two conditions, solution of equilibrium biomass, effort and harvest at static MEY for both shrimp (s) and fish (f) fisheries are derived separately. The derivation of the solution is presented in Appendix F. The solution for equilibrium biomass $\left(B^{static}\right)$, effort $\left(E^{static}\right)$ and harvest $\left(h^{static}\right)$ for both shrimp (s) and fish (f) fisheries at the static MEY are reported in the Table 4.2.

Table 4.2 **Solution: static MEY**

Shrimp fishery	Fish fishery
$B_s^{static} = \frac{w^s}{p^s q^s}\left(\frac{r^s}{q^s E^s - r^s}\right)$	$B_f^{static} = \frac{w^f}{p^f q^f}\left(\frac{r^f}{q^f E^f - r^f}\right)$
$E_s^{static} = \frac{r^s}{q^s}\left(1 - \frac{w^s}{p^s q^s B^s}\right)$	$E_f^{static} = \frac{r^f}{q^f}\left(1 - \frac{w^f}{p^f q^f B^f}\right)$
$h_s^{static} = \frac{w^s r^s E^s}{p^s\left(q^s E^s - r^s\right)}$	$h_f^{static} = \frac{w^f r^f E^f}{p^f\left(q^f E^f - r^f\right)}$

Source: Author's calculation

Using the solution, total revenue from harvest $\left(TR^{static}\right)$, total cost of harvest $\left(TC^{static}\right)$ and total profit $\left(\pi^{static}\right)$ at the static MEY of both shrimp (s) and fish (f) fisheries are obtained.

4.3.5 Dynamic MEY

The optimal harvest policies, that is, the dynamic MEY for both shrimp (s) and fish (f) fisheries of industrial marine fisheries of Bangladesh are solved by maximizing the present value of profit of these two fisheries separately:

$$Max\int_0^\infty e^{-\rho t}\left(p^s q^s B^s - w^s\right)E^s.dt \quad \text{subject to:} \quad \begin{cases} \dfrac{dB^s}{dt} = r^s B^s \ln\left(\dfrac{K^s}{B^s}\right) - q^s E^s B^s \\ B^s(0) = B_0^s \\ 0 \le E^s(t) \le E_{\max}^s \end{cases} \tag{4.19}$$

$$Max\int_0^\infty e^{-\rho t}\left(p^f q^f B^f - w^f\right)E^f.dt \quad \text{subject to:} \quad \begin{cases} \dfrac{dB^f}{dt} = r^f B^f \ln\left(\dfrac{K^f}{B^f}\right) - q^f E^f B^f \\ B^f(0) = B_0^f \\ 0 \le E^f(t) \le E_{\max}^f \end{cases} \tag{4.20}$$

The separate current value Hamiltonian for both shrimp (s) and fish (f) fisheries are:

$$H^c\left(E^s, B^s\right) = \left(p^s q^s B^s - w^s\right)E^s + \mu\left[r^s B^s \ln\left(\frac{K^s}{B^s}\right) - q^s E^s B^s\right] \tag{4.21}$$

$$H^c\left(E^f, B^f\right) = \left(p^f q^f B^f - w^f\right)E^f + \mu\left[r^f B^f \ln\left(\frac{K^f}{B^f}\right) - q^f E^f B^f\right] \tag{4.22}$$

The optimum solution of a present value-maximizing problem satisfies the following maximum principles:

(i) $\dfrac{\partial H^c}{\partial E} = 0$

(ii) $\dfrac{\partial H^c}{\partial \mu} = \dot{B}$

(iii) $\dot{\mu} - \rho\mu = -\dfrac{\partial H^c}{\partial B}$

The first maximum principle gives the following equations for both shrimp (s) and fish (f) fisheries:

$$\mu^s = p^s - \frac{w^s}{q^s B^s} \text{ and } \mu^f = p^f - \frac{w^f}{q^f B^f} \tag{4.23}$$

At steady-state, $\dot{B} = \dot{\mu} = 0$. Solving the second maximum principles, $q^s E^s = r^s \ln\left(\dfrac{K^s}{B^s}\right)$ and $q^f E^f = r^f \ln\left(\dfrac{K^f}{B^f}\right)$ are derived for both shrimp (s) and fish (f) fisheries separately. Substituting $q^s E^s = r^s \ln\left(\dfrac{K^s}{B^s}\right)$ and $q^f E^f = r^f \ln\left(\dfrac{K^f}{B^f}\right)$ in the third maximum principle for shrimp (s) and fish (f) fisheries respectively, following equations for both shrimp (s) and fish (f) fisheries are obtained:

$$\mu^s = \left(\frac{p^s q^s}{\rho + r^s}\right) E^s \text{ and } \mu^f = \left(\frac{p^f q^f}{\rho + r^f}\right) E^f \tag{4.24}$$

Using Equation 4.23 and 4.24, solutions for optimal biomass, effort and harvest are derived separately for both shrimp (s) and fish (f) fisheries. The derivation of these solutions is presented in Appendix G. The solution for equilibrium biomass $\left(B^{dynamic}\right)$, effort $\left(E^{dynamic}\right)$ and harvest $\left(h^{dynamic}\right)$ for both shrimp (s) and fish (f) fisheries at the dynamic MEY are reported in the Table 4.3.

Table 4.3 **Solution: dynamic MEY**

Shrimp fishery	Fish fishery
$B_s^{dynamic} = \dfrac{w^s(\rho + r^s)}{p^s q^s[(\rho + r^s) - q^s E^s]}$	$B_f^{dynamic} = \dfrac{w^f(\rho + r^f)}{p^f q^f[(\rho + r^f) - q^f E^f]}$
$E_s^{dynamic} = \left(\dfrac{\rho + r^s}{p^s q^s}\right)\left(p^s - \dfrac{w^s}{q^s B^s}\right)$	$E_f^{dynamic} = \left(\dfrac{\rho + r^f}{p^f q^f}\right)\left(p^f - \dfrac{w^f}{q^f B^f}\right)$
$h_s^{dynamic} = \dfrac{w^s(\rho + r^s)E^s}{p^s[(\rho + r^s) - q^s E^s]}$	$h_f^{dynamic} = \dfrac{w^f(\rho + r^f)E^f}{p^f[(\rho + r^f) - q^f E^f]}$

Source: Author's calculation

Using the solution, total revenue from harvest $(TR^{dynamic})$, total cost of harvest $(TC^{dynamic})$ and total profit $(\pi^{dynamic})$ at the dynamic MEY of both shrimp (s) and fish (f) fisheries are obtained.

4.3.6 Maximum Sustainable Yield (MSY)

Equilibrium biomass, effort and harvest at the Maximum Sustainable Yield (MSY) for both shrimp (s) and fish (f) fisheries derived in Chapter 3 (Appendix D) are used to compare the result of the bio-economic equilibrium (BE), static and dynamic MEY for both shrimp (s) and fish (f) fisheries. The solution for biomass (B^{static}), effort (E^{static}) and harvest (h^{static}) for both shrimp (s) and fish (f) fisheries at the MSY derived in Chapter 3 (Appendix D) are reported in the Table 4.4. Using the solution, total revenue from harvest (TR^{MSY}), total cost of harvest (TC^{MSY}) and total profit (π^{MSY}) at the MSY of both shrimp (s) and fish (f) fisheries are obtained.

Table 4.4 **Solution: MSY**

Shrimp fishery	Fish fishery
$B_s^{MSY} = \dfrac{K^s}{2.72}$	$B_f^{MSY} = \dfrac{K^f}{2.72}$
$E_s^{MSY} = \dfrac{r^s}{q^s}$	$E_f^{MSY} = \dfrac{r^f}{q^f}$
$h_s^{MSY} = \dfrac{r^s K^s}{2.72}$	$h_f^{MSY} = \dfrac{r^f K^f}{2.72}$

Source: Author's calculation

4.4 Data

The growth rate of the biomass and the shape of the growth of both shrimp and fish fisheries of industrial marine fisheries of Bangladesh relies on the two biological parameters: r and K, where r is the intrinsic growth rate and K is the maximum stock level or virgin biomass. Following CY&P models (Clarke et al 1992) and applying Ordinary Least Squares (OLS) technique, the value of r, q and K are calculated in Chapter 3 of this research, which are used in this study. The calculated values of r, q and K for the shrimp fishery are 1.56246156, 0.00026675 and 5533 tonnes respectively and for the fish fishery are 1.01661534, 0.00011764 and 68425 tonnes respectively.

To calculate the total cost function both fixed and variable inputs are used. The fixed input is the average total engine power per year, which is a simple multiplication of average engine power per vessel and average total number of vessels in the fleet per year. Data for both engine power and number of vessels are collected from MFD (2009). The calculated average engine power per vessel of both shrimp and fish fleet are drawn from Chapter 2 of this research. The calculated average engine power of shrimp and fish vessels are 664 Brake Horse Power (BHP) and 694 BHP, respectively. The number of vessels in both shrimp and fish vessels varies between 1993 and 2006. As there is a significant variation of the number of vessels in the fleet between two periods (1993-2000 and 2001-2006), the average total number of vessels in the fleet per year for the period 2001-2006 is used in this study. Data shows that in the period 2001-2006, the average number of vessels per year in shrimp and fish fleets is 44 and 50 per year, respectively. The calculated average of the total engine power per year in shrimp and fish fisheries are 29,327 BHP and 34, 931 BHP, respectively.

Two variable inputs, average total crew per year and average total fishing days per year are used in the total cost function. The average total crew per year is also derived from a simple multiplication of average number of crew per vessel per year and average number of vessels in the fleet per year. Data for the number of total crew is also collected from MFD (2009). The calculated average number of crew per vessel of shrimp and fish vessels is 32 and 30 per year, respectively and drawn from Chapter 2 of this research. The calculated average of the total crew per year in shrimp and fish fisheries is 1413 and 1510, respectively.

The average total fishing days per year is also derived from a simple multiplication of average total fishing days per vessel per year and average number of vessels in the fleet per year. Data for the number of total fishing days is also collected from MFD (2009). The calculated average fishing days per vessel of shrimp and fish vessels is 175 and 169 days per year, respectively and drawn from Chapter 2 of this research. The calculated average of the total fishing days per year in shrimp and fish fisheries is 7729 and 8506, respectively.

To calculate three input prices of the total cost function, real wage rate index of fisheries sector in Bangladesh is collected from Bangladesh Economic Review (MoF 2012) and used for input prices of crew. The calculated marginal value product of engine power, crew and fishing days of vessels in the shrimp fleet are 0.16, 0.53 and 0.39, respectively and in the fish fleet are 0.44, 0.45 and 0.61, respectively. All these values of the marginal products are drawn from Chapter 2 of this research. Using real wage rate index and marginal value product of three inputs (engine power, crew and fishing days), the input price index of engine power and fishing days are calculated. Thus the calculated input price index of engine power, crew and fishing days in the shrimp fishery are 36, 118 and 87 respectively. On the other hand, the calculated input price index of engine power, crew and fishing days in the fish fishery are 115, 118 and 160 respectively.

The cost per unit of effort is calculated using total costs described above and total effort. The average of the total fishing days per year is considered as effort. The calculated average of the total effort per year in shrimp and fish fisheries is 7729 and 8506 vessel days, respectively. The calculated cost per unit of effort for shrimp and fish fisheries is 244 and 655, respectively. Price of harvest for both shrimp and fish fishery is calculated using long run equilibrium condition, where price is equal to the average cost. Hence, the average cost of harvest is calculated to find out the price of harvest for both shrimp and fish fisheries. The average cost of harvest is calculated using the ratio of total cost of harvest and the amount of total harvest. Input price index is used to measure input cost of the total cost of harvest, hence the calculated price of harvest for both shrimp and fish fishery is also an index. The calculated price index for both shrimp and fish fisheries is 582 and 333, respectively.

For optimal solution, both average deposit rate per year (6.92%) and average lending rate per year (12.41%) for the period 2001-2006 are used as the Social Discount Rates (SDRs) and both the SDRs are used for both shrimp and fish fisheries. Both average deposit rate per year and average lending rate per year are collected from the Bangladesh Economic Review (MoF 2012). For sensitivity analysis, different social discount rates (30%, 25%, 20%, 15%, 10%, 5%, 3%, 1% and 0%) are used and these social discount rates are taken as arbitrary.

The value of all variables and the value of parameters of those used in this study are reported in the Table 4.5.

Table 4.5 **Variables and the parameters**

	Shrimp	Fish
Total engine power per year (BHP)	29327	34931
Total crew per year (number)	1413	1510
Total fishing days per year (days)	7729	8506
Factor price index of inputs (engine power)	36	115
Factor price index of inputs (crew)	118	118
Factor price index of inputs (fishing days)	87	160
Cost per unit of effort (index)	244	655
Price index of harvest	582	333
Total harvest per year (tonnes)	3237	16702
Total vessels per year (number)	44	50
Intrinsic growth rate	1.56246156	1.016615339
Cathability coefficient	0.000266751	0.00011764
Virgin biomass (tonnes)	5533	68425

Source: Author's calculation.

4.5 Results and sensitivity analysis

The bio-economic equilibrium (BE) for both open access shrimp and fish fisheries are calculated separately using the solution obtained in Appendix E. Equilibrium at static MEY and dynamic MEY are calculated using the solutions obtained in Appendix F and G, respectively. For both open access shrimp and fish fisheries, the bio-economic equilibrium (BE) is obtained by setting profit equal to zero and the equilibrium at the static MEY is obtained from a profit maximization problem. On the other hand, the equilibrium at dynamic MEY is obtained through a present value-maximization problem. The present value of profit is maximized separately through a choice of effort subject to the constraints imposed by the biological growth models of shrimp and fish. The equilibrium at static and dynamic MEY, and the bio-economic equilibrium of open access fishery are compared with the equilibrium at the Maximum Sustainable Yield (MSY). All equilibrium values of both shrimp and fish fishery and sensitivity results are obtained using Microsoft Office EXCEL 2007 software. Results of open-access BE; static & dynamic MEY; and MSY for both shrimp and fish fisheries are reported in the Table 4.6.

Table 4.6 **Results: BE, MEY and MSY**

	BE	MEY (Static)	MEY (Dynamic)		MSY
			SDR=6.92%	SDR=12.41%	
Shrimp fishery					
Biomass (tonnes)	1570	6049	5396	5000	2034
Effort (vessel days)	7378	4337	4337	4337	5857
Harvest (tonnes)	3090	6999	6243	5784	3178
Total revenue (value)	1796975	4070053	3630766	3363917	1848304
Total cost (value)	1796975	1056384	1056384	1056384	1426680
Profit (value)	0	3013668	2574382	2307532	421624
Number of vessels	42	25	25	25	33
Fish fishery					
Biomass (tonnes)	16690	40618	37218	35138	25156
Effort (vessel days)	12193	5091	5091	5091	8642
Harvest (tonnes)	23940	24325	22289	21043	25574
Total revenue (value)	7982592	8111165	7432117	7016779	8527583
Total cost (value)	7982592	3332945	3332945	3332945	5657768
Profit (value)	0	4778220	4099172	3683835	2869814
Number of vessels	72	30	30	30	51

Note: SDR= Social Discount Rate. For dynamic MEY, SDR: 6.92% is the average deposit rate per year and SDR: 12.41% is the average lending rate per year in Bangladesh.
BE= Bio-economic Equilibrium of the open access fishery
MEY= Maximum Economic Yield
MSY= Maximum Sustainable Yield
Source: Author's calculation.

For the dynamic models presented in Table 4.6, both average deposit rate per year (6.92%) and average lending rate per year (12.41%) of Bangladesh are used as the social discount rate (ρ). The price index of harvest (p) for shrimp (582) and fish (333); and the cost per unit effort (w) of harvesting shrimp (244) and fish (655); and the catchability coefficient (q) for shrimp (0.00026675) and fish (0.00011764) are used. The price index of harvest (p) shows that shrimp is high-valued biomass and fish is low-valued biomass. On the other hand, cost per unit effort (w) of harvesting shrimp is low compared to the harvesting fish. In the shrimp fishery, the price index of shrimp (p) is higher than the cost per unit effort (w) of harvesting shrimp, but in the fish fishery, the cost per unit effort (w) of harvesting fish is higher than the price index of harvest (p). The cost per unit effort (w) of harvesting fish may be higher may be due to the declining trend of technical change of fish vessels as reported in the Chapter 2 of this research.

The results in Table 4.6 show that effort at bio-economic equilibrium (BE) of both open access shrimp and fish fisheries is higher than effort at both static and dynamic MEY and MSY levels; biomass and profit at the BE are lower than both static and dynamic MEY and MSY levels. The results indicate that in open-access industrial fisheries in Bangladesh, excessive use of efforts makes both shrimp and fish fisheries economically inefficient in the form of low stock biomass and profit. On the other hand, the biomass at both static and dynamic MEY is higher than the biomass at the MSY level. The result is consistent with Gordon (1954), which shows that biomass at the MEY is always greater than MSY in a static framework. But, in a dynamic framework, there is an ongoing debate about whether MEY is greater or smaller than MSY. A dynamic framework with zero discount rate is developed by Smith (1969) and shows that biomass at the MEY is always greater than MSY. Clark (1973), Clark & Munro (1975) and others also develop dynamic frameworks, albeit in an inter-temporal setting with discounting. Studies show that biomass at the dynamic MEY could be less than MSY level with a high enough discount rate (Clark 1973). The dynamic MEY could be either greater or smaller than MSY depending on some factors: discount rate, sensitivity of costs and revenues to biomass and harvest, and the marginal growth in biomass (Clark & Munro 1975). The dynamic MEY could exceed the MSY level under a range of conditions: with a variable stock effect, technological change, with an increase in the cost per unit effort, when the discount rate exceeds the intrinsic growth rate (Grafton et al 2010).

However, results in Table 4.6 show that by setting biomass target at the MEY will give an economically viable (with high profit) and ecologically sustainable (with high stock biomass) shrimp and fish fisheries in Bangladesh. Grafton et al (2010) shows that MEY has *"…the potential to generate a 'win-win' that increases both economic profits and the size of the fishery whenever the current biomass is the less than dynamic MEY."*

Recent studies also show that the MEY target is considered as an efficient management target, because it protects resources, guarantees sustainability and maximizes economic yield (Grafton et al 2006). The study on Australian Northern prawn fishery (Kompas et al 2010) and Western and Central Pacific tuna fishery (Kompas & Che 2006) also show similar arguments in favor of the MEY target, suggesting the importance of conserving stocks for profitability.

4.5.1 Sensitivity analysis

The equilibrium biomass at static MEY- $B=\frac{w}{pq}\left(\frac{r}{qE-r}\right)$, dynamic MEY- $B=\frac{w(\rho+r)}{pq[(\rho+r)-qE]}$) and the bio-economic equilibrium of open access fishery- $B=\frac{w}{pq}$ of this study depends on price of harvest (p); cost per unit effort (w) and catchability coefficient (q). In addition to that both static and dynamic MEY depends on the intrinsic growth rate (r) and efforts level (E). Dynamic MEY also depends on another factor: social discount rate (ρ). Sensitivity of biomass to the changes in price of harvest (p), changes in cost per unit effort (w) and changes in social discount rate (ρ) on shrimp and fish stock biomasses are examined, but the study doesn't cover the sensitivity to changes in catchability coefficient; the intrinsic growth rate and efforts level.

The sensitivity to changes in price of harvest (p); changes in cost per unit effort (w) and changes in social discount rate (ρ) of biomass at dynamic MEY and sensitivity to changes in price of harvest (p) and changes in cost per unit effort (w) of both biomass at static MEY and biomass at BE are found using comparative static analysis presented in Table 4.7.

Table 4.7 **Comparative static analysis**

	Dynamic MEY	Static MEY	BE
Changes in price of harvest (p)	$\frac{dB}{dp}=-\frac{w(\rho+r)}{p^2q[(\rho+r)-qE]}<0$	$\frac{dB}{dp}=-\frac{wr}{p^2q(qE-r)}<0$	$\frac{dB}{dp}=-\frac{w}{p^2q}<0$
Changes in cost per unit effort (w)	$\frac{dB}{dw}=\frac{(\rho+r)}{pq[(\rho+r)-qE]}>0$	$\frac{dB}{dw}=\frac{r}{pq(qE-r)}>0$	$\frac{dB}{dw}=\frac{1}{pq}>0$
Changes in social discount rate (ρ)	$\frac{dB}{d\rho}=-\frac{wE}{p[(\rho+r)-qE]^2}<0$	-	-

Note: BE= Bio-economic Equilibrium of the open access fishery and MEY= Maximum Economic Yield
Source: Author's calculation.

Changes in price of harvest (p)**:** Table 4.7 shows that equilibrium biomass at BE, static and dynamic MEY are all sensitive to the changes in price of harvest (p), which is inversely related. The inverse relation of sensitivity of biomass to the changes in price of harvest (p) shows that biomass falls with the increase in price of harvest (p) and biomass rebuilds with the decrease in price of harvest (p). The sensitivity results to the changes in price of harvest (p) for both shrimp and fish fisheries are reported in Table 4.8. The results show that both shrimp and fish biomasses are sensitive to the change in price of harvest. Results also show that with fixed unit cost of effort (w) and changes in price of harvest (p), both shrimp and fish biomasses at the bio-economic equilibrium (BE) are lower than both static & dynamic MEY, and MSY levels. Sensitivity results in Table 4.8 also show that with both an increase and a decrease in price of harvest (p), both shrimp and fish biomasses at the static and dynamic MEY exceed the MSY level.

Table 4.8 **Sensitivity of shrimp and fish biomasses: changes in p and fixed w**

	SDR (%)	Shrimp stock biomass (tonnes)			Fish stock biomass (tonnes)		
		$p = p_0$	$p = p_1 > p_0$ $(\uparrow p)$	$p = p_2 < p_0$ $(\downarrow p)$	$p = p_0$	$p = p_1 > p_0$ $(\uparrow p)$	$p = p_2 < p_0$ $(\downarrow p)$
BE		1570	1339	1894	16690	12853	23885
MEY (static)		6049	5158	7299	40618	31279	58128
MEY	6.92	5396	4602	6511	37218	28661	53262
(dynamic)	12.41	5000	4263	6032	35138	27059	50285
MSY		2034	2034	2034	25156	25156	25156

Note: SDR= Social Discount Rate. For dynamic MEY, SDR: 6.92% is the average deposit rate per year and SDR: 12.41% is the average lending rate per year in Bangladesh.
BE= Bio-economic Equilibrium of the open access fishery
MEY= Maximum Economic Yield
MSY= Maximum Sustainable Yield
Source: Author's calculation.

Changes in cost per unit effort (w)**:** Table 4.7 shows that equilibrium biomass at BE, static and dynamic MEY are all sensitive to the changes in cost per unit effort (w), which is positively related. The positive relation of sensitivity of biomass to the changes in cost per unit effort (w) shows that biomass rebuilds with the increase in cost per unit effort (w) and biomass falls with the decrease in cost per unit effort (w). The sensitivity results to the changes in cost per unit effort (w) for both shrimp and fish fisheries are reported in Table 4.9. The sensitivity results in Table 4.9 show that both shrimp and fish biomasses are sensitive to the change in cost per unit effort (w). Results show that with fixed price of harvest (p) and changes in cost per unit effort (w), fish biomass at the bio-economic equilibrium (BE) are lower than both static and dynamic MEY and MSY levels. On the other hand, with fixed price of harvest (p) and changes in cost per unit effort (w), shrimp biomass at the bio-economic equilibrium (BE) is lower than both static and dynamic MEY. But, higher with increase in cost per unit effort (w) and lower with decrease in cost per unit effort (w) compare to MSY levels. Sensitivity results in Table 4.9 also show that with both increase and decrease in cost per unit effort (w), both shrimp and fish biomasses at the static and dynamic MEY exceed the MSY level.

Table 4.9 **Sensitivity of shrimp and fish biomasses: changes in w and fixed p**

	SDR (%)	Shrimp stock biomass (tonnes)			Fish stock biomass (tonnes)		
		$w = w_0$	$w = w_1 > w_0$ $(\uparrow w)$	$w = w_2 < w_0$ $(\downarrow w)$	$w = w_0$	$w = w_1 > w_0$ $(\uparrow w)$	$w = w_2 < w_0$ $(\downarrow w)$
BE		1570	2218	928	16690	19247	14149
MEY (static)		6049	8544	3576	40618	46841	34433
MEY (dynamic)	6.92	5396	7622	3190	37218	42919	31550
	12.41	5000	7061	2956	35138	40521	29787
MSY		2034	2034	2034	25156	25156	25156

Note: SDR= Social Discount Rate. For dynamic MEY, SDR: 6.92% is the average deposit rate per year and SDR: 12.41% is the average lending rate per year in Bangladesh.
BE= Bio-economic Equilibrium of the open access fishery
MEY= Maximum Economic Yield
MSY= Maximum Sustainable Yield
Source: Author's calculation**.**

Changes in social discount rate (ρ)**:** Table 4.7 shows that only the equilibrium biomass at dynamic MEY is sensitive to the changes in social discount rate (ρ), which is inversely related and shows that the higher the discount rate the lower the biomass, that is, the high discount rates have the effect of causing biological overexploitation (Clark 1973). To see the sensitivity of change in biomass at the dynamic MEY compare to the MSY level, nine different cases are examined, where nine combinations of fixed and variable price of harvest (p) and cost per unit effort (w) are used with changes in social discount rate (ρ). The sensitivity results to the changes in social discount rate (ρ) with fixed and variable price of harvest (p) and cost per unit effort (w) for both shrimp and fish fisheries are reported in Table 4.10. The sensitivity results show that the higher the discount rate the lower the biomass for both shrimp and fish fisheries. Sensitivity results also show that in all cases, shrimp biomass at the dynamic MEY exceeds the MSY level. But, fish biomass at the dynamic MEY exceeds the MSY level except two situations. Fish biomass at the MSY is higher than dynamic MEY at higher discount rates with the combination of (i) higher price of harvest (p) and fixed cost per unit effort (w); and (ii) higher price of harvest (p) and lower cost per unit effort (w).

Table 4.10 **Sensitivity of shrimp and fish biomasses: changes in** ρ

SDR	MEY (dynamic)											MSY
	0	0.01	0.03	0.05	0.0692	0.1	0.1241	0.15	0.2	0.25	0.3	
A. Shrimp biomass (tonnes)												
Case-1	6049	5942	5741	5558	5396	5163	5000	4840	4570	4341	4145	2034
Case-2	5158	5066	4895	4739	4602	4403	4263	4127	3897	3702	3534	2034
Case-3	7299	7169	6926	6706	6511	6230	6032	5840	5514	5238	5001	2034
Case-4	8544	8391	8108	7849	7622	7292	7061	6836	6454	6131	5854	2034
Case-5	3576	3513	3394	3286	3190	3053	2956	2861	2702	2567	2450	2034
Case-6	7285	7155	6914	6693	6499	6218	6021	5829	5504	5228	4992	2034
Case-7	3050	2995	2894	2802	2720	2603	2521	2440	2304	2188	2089	2034
Case-8	10308	10125	9782	9470	9196	8798	8520	8247	7787	7397	7063	2034
Case-9	4315	4238	4095	3964	3849	3683	3566	3452	3260	3097	2956	2034
B. Fish biomass (tonnes)												
Case-1	40618	40059	39015	38060	37218	35997	35138	34296	32871	31660	30617	25156
Case-2	31279	30848	30045	29309	28661	27720	27059	26411	25313	24380	23577	25156
Case-3	58128	57328	55834	54468	53262	51514	50285	49081	47042	45308	43815	25156
Case-4	46841	46196	44992	43891	42919	41511	40521	39550	37907	36510	35307	25156
Case-5	34433	33958	33073	32264	31550	30515	29787	29073	27865	26838	25954	25156
Case-6	36071	35574	34647	33800	33051	31967	31204	30457	29191	28115	27189	25156
Case-7	26516	26151	25469	24846	24296	23499	22938	22389	21459	20668	19987	25156
Case-8	67033	66110	64387	62812	61421	59406	57989	56600	54248	52249	50528	25156
Case-9	49276	48598	47331	46173	45151	43669	42628	41607	39878	38408	37143	25156

Note:
Case-1: both p and w are fixed
Case-2: increases in p and fixed w
Case-3: decreases in p and fixed w
Case-4: fixed p and increases in w
Case-5: fixed p and decreases in w
Case-6: increases in both p and w
Case-7: increases in p and decreases in w
Case-8: decreases in p and increases in w
Case-9: decreases in both p and w

Note: SDR= Social Discount Rate; MEY= Maximum Economic Yield and MSY= Maximum Sustainable Yield
Source: Author's calculation.

4.6 Conclusion

This study measures the economic performance of the industrial marine fisheries of Bangladesh. The industrial marine fisheries of Bangladesh are open access fisheries and the industrial fishing fleets of Bangladesh have been expanding over time. This study covers commercially important two fisheries: shrimp and fish, harvested by two different fishing fleets. This study develops two single-species and single-fleet models separately for both shrimp and fish fisheries. Current and potential economic performances of both shrimp and fish fisheries in this study are measured using three different bio-economic models: a bio-economic model for open access fishery, a static profit maximization problem and a dynamic present value-maximization problem in continuous time. A harvest function given by Scheafer (1954) and Munro (1981, 1982) is used in this study. For both shrimp and fish fisheries of the industrial marine fisheries of Bangladesh, this is the first study that uses Gompertz curve (Richards 1959) in the biological growth models and biological parameters are derived following CY&P models (Clarke et al 1992); price of harvest and cost per unit effort are estimated separately. The equilibrium biomass, effort and profit at bio-economic equilibrium of open access fishery, at static MEY and dynamic MEY are compared with the Maximum Sustainable Yield (MSY). Sensitivity to changes in price of harvest; changes in cost per unit effort and changes in social discount rate on biomass are also examined.

The estimated results show that effort at bio-economic equilibrium (BE) of both open access shrimp and fish fisheries are higher than effort at static MEY, dynamic MEY and MSY levels; both biomass and profit at the BE are lower than static MEY, dynamic MEY and MSY levels. Results also show that biomass at both static and dynamic MEY exceeds the biomass at the MSY level. The sensitivity results show that both shrimp and fish biomasses are sensitive to the changes in price of harvest, changes in cost per unit effort and changes in social discount rates. Both shrimp and fish biomasses both at static and dynamic MEY exceed MSY levels in response to both the changes in price of harvest and changes in cost per unit effort. Similarly, sensitivity results show that both shrimp and fish biomasses at MSY exceed open access BE levels in response to both the changes in price of harvest and changes in cost per unit effort except one situation for shrimp fishery. Biomass at the open access BE of the shrimp fishery can exceed MSY level when cost per unit effort increases with fixed price of harvest. On the other hand, with different social discount rates, both shrimp and fish biomasses at dynamic MEY level exceed MSY levels depending on both the changes in price of harvest and changes in cost per unit effort except two situations for fish fishery. Results show that with high social discount rates, fish biomass at dynamic MEY is lower than MSY when either increases in both price of harvest and cost per unit effort or price of harvest increases with fixed cost per unit effort. In general, results confirm that the higher the discount rate the lower the biomass for both shrimp and fish fisheries. That is, with higher discount rates biological overexploitation occurs.

Results indicate that in Bangladesh industrial fisheries, excessive use of effort makes both shrimp and fish fisheries economically inefficient in the form of low stock biomass and profit. The study suggests that both economically viable (with high profit) and ecologically sustainable (with high stock biomass) shrimp and fish fisheries in industrial marine fisheries of Bangladesh could be achieved by setting management target at the MEY level and hence excessive use of efforts in both shrimp and fish fisheries needs to be reduced. The effort use in this study is the multiplication of the number of vessels and the number of fishing days per year. So, to reduce the excessive use of effort a reduction in number of vessels in both fleets are needed by keeping the fishing days per year per vessels constant that is, 175 days per year per vessel for shrimp fleet and 169 days per year per vessel for fish fleet. As MEY captures both biological and economic factors, it would help to rebuild stock biomass and to maximize the profit of the shrimp and fish fisheries of Bangladesh.

Appendix E

Derivation of the solution of bio-economic equilibrium of open access fishery

In the absence of harvest, biological growth of biomass:

$$\frac{dB}{dt} = rB\ln\left(\frac{K}{B}\right) \tag{E1}$$

Harvest function:

$$h = qEB \tag{E2}$$

With harvest, biological growth of biomass:

$$\frac{dB}{dt} = rB\ln\left(\frac{K}{B}\right) - h \tag{E3}$$

At steady-state,

$$\left.\begin{aligned}
&\frac{dB}{dt} = 0 \Rightarrow rB\ln\left(\frac{K}{B}\right) = h \\
&\Rightarrow \frac{h}{B} = r\ln\left(\frac{K}{B}\right) \\
&\Rightarrow \frac{qEB}{B} = r\ln\left(\frac{K}{B}\right) \\
&\Rightarrow qE = r\ln\left(\frac{K}{B}\right) \\
&\Rightarrow \frac{K}{B} = e^{\frac{qE}{r}}
\end{aligned}\right| \tag{E4}$$

Solving Equation E4, gives the equilibrium biomass (eq) as a function of fishing effort is obtained:

$$B_{eq} = Ke^{-\frac{qE}{r}} \tag{E5}$$

Substituting $B_{eq} = Ke^{-\frac{qE}{r}}$ into Equation E2 equilibrium harvest as a function of effort can be obtained:

$$h_{eq} = qEKe^{-\frac{qE}{r}} \tag{E6}$$

Equation E6 represents the long-term production function of the fishery.

The economic rent/profit of the fishery can be defined as:

$$\left.\begin{aligned} &\pi = TR - TC \\ &\Rightarrow \pi = ph - wE \\ &\Rightarrow \pi = (pqB - w)E \end{aligned}\right| \tag{E7}$$

In an open access fishery, equilibrium occurs when total revenue of harvest equals total cost of harvest and thus $\pi = 0$, where there is no stimulus for entry and exit to the fishery:

$$\left.\begin{aligned} &\pi = 0 \\ &\Rightarrow TR = TC \\ &\Rightarrow pqBE = wE \end{aligned}\right| \tag{E8}$$

Solving Equation E8, the biomass at the bio-economic equilibrium (BE) for an open access fishery is obtained:

$$B_{BE} = \frac{w}{pq} \tag{E9}$$

From Equation E4,

$$E = \frac{r}{q}\ln\left(\frac{K}{B}\right) \tag{E10}$$

Substituting $B_{BE} = \frac{w}{pq}$ into $E = \frac{r}{q}\ln\left(\frac{K}{B}\right)$, the effort at the bio-economic equilibrium (BE) for an open access fishery is obtained:

$$E_{BE} = \frac{r}{q}\ln\left(\frac{pqK}{w}\right) \tag{E11}$$

Substituting $B_{BE} = \frac{w}{pq}$ and $E_{BE} = \frac{r}{q}\ln\left(\frac{pqK}{w}\right)$ into Equation E2, the harvest at the bio-economic equilibrium (BE) for an open access fishery is obtained:

$$h_{BE} = \frac{wr}{pq}\ln\left(\frac{pqK}{w}\right) \tag{E12}$$

So, the biomass, effort and harvest at the bio-economic equilibrium (BE) for an open access fishery are:

Biomass: $B_{BE} = \frac{w}{pq}$

Effort: $E_{BE} = \frac{r}{q}\ln\left(\frac{pqK}{w}\right)$

Harvest: $h_{BE} = \frac{wr}{pq}\ln\left(\frac{pqK}{w}\right)$

Appendix F

Derivation of the solution of static MEY

In the absence of harvest, biological growth of biomass:

$$\frac{dB}{dt} = rB\ln\left(\frac{K}{B}\right) \tag{F1}$$

Harvest function:

$$h = qEB \tag{F2}$$

With harvest, biological growth of biomass:

$$\frac{dB}{dt} = rB\ln\left(\frac{K}{B}\right) - h \tag{F3}$$

At steady-state, $\frac{dB}{dt} = 0$

$$\Rightarrow rB\ln\left(\frac{K}{B}\right) = h \tag{F4}$$

Total revenue:

$$TR = ph \tag{F5}$$

Total cost:

$$TC = wE \tag{F6}$$

The economic rent/profit of the fishery is:

$$\pi = TR - TC \tag{F7}$$

From Equation F4, the equilibrium effort and biomass are obtained:

$$E_{eq} = \frac{r}{q}\ln\left(\frac{K}{B}\right) \tag{F8}$$

$$B_{eq} = Ke^{-\frac{qE}{r}} \tag{F9}$$

Substituting $E_{eq} = \frac{r}{q}\ln\left(\frac{K}{B}\right)$ and $B_{eq} = Ke^{-\frac{qE}{r}}$ into Equation F2, the equilibrium harvest is obtained:

$$h_{eq} = qEKe^{-\frac{qE}{r}} \tag{F10}$$

Substituting $h_{eq} = qEKe^{-\frac{qE}{r}}$ into Equation F5, the total revenue as a function of effort is obtained:

$$TR = pqEKe^{-\frac{qE}{r}} \tag{F11}$$

Substituting $TR = pqEKe^{-\frac{qE}{r}}$ and $TC = wE$ into Equation F7, the economic rent/profit is obtained:

$$\pi(E) = pqEKe^{-\frac{qE}{r}} - wE \tag{F12}$$

The maximization problem is:

$$\text{Max } \pi(E) = pqEKe^{-\frac{qE}{r}} - wE \tag{F13}$$

MEY is the equilibrium level, where the economic rent/profit is maximized. The equilibrium occurs when marginal revenue equals marginal cost and the first-order necessary condition for maximum profit is, $\frac{d\pi}{dE} = 0$.

Solving $MR = MC$,

$$\Rightarrow pqKe^{-\frac{qE}{r}}\left[1 - \frac{qE}{r}\right] = w \tag{F14}$$

$$\Rightarrow pqB\left[1 - \frac{qE}{r}\right] = w \tag{F15}$$

$$\Rightarrow B = \frac{w}{pq\left[1 - \frac{qE}{r}\right]}$$

$$\Rightarrow B = \frac{w}{pq}\left(\frac{r}{r - qE}\right)$$

$$\Rightarrow \left|B_{static\_MEY}\right| = \frac{w}{pq}\left(\frac{r}{qE - r}\right)$$

Solving Equation F15,

$$\Rightarrow 1 - \frac{qE}{r} = \frac{w}{pqB}$$

$$\Rightarrow \frac{qE}{r} = 1 - \frac{w}{pqB}$$

$$\Rightarrow E_{static\_MEY} = \frac{r}{q}\left(1 - \frac{w}{pqB}\right)$$

Substituting $E_{static\_MEY} = \frac{r}{q}\left(1 - \frac{w}{pqB}\right)$ and $\left|B_{static\_MEY}\right| = \frac{w}{pq}\left(\frac{r}{qE - r}\right)$ into Equation F2 $(h = qEB)$, the equilibrium harvest at static MEY is obtained:

$$\Rightarrow h_{static\_MEY} = \frac{wrE}{p(qE - r)}$$

So, the equilibrium biomass, effort and harvest at the static MEY are:

Biomass: $$\left|B_{static\_MEY}\right| = \frac{w}{pq}\left(\frac{r}{qE - r}\right)$$

Effort: $$E_{static\_MEY} = \frac{r}{q}\left(1 - \frac{w}{pqB}\right)$$

Harvest: $$h_{static\_MEY} = \frac{wrE}{p(qE - r)}$$

Appendix G

Derivation of the solution of dynamic MEY

In the absence of harvest, biological growth of biomass:

$$\frac{dB}{dt} = rB\ln\left(\frac{K}{B}\right) \tag{G1}$$

Harvest function:

$$h = qEB \tag{G2}$$

With harvest, biological growth of biomass:

$$\frac{dB}{dt} = rB\ln\left(\frac{K}{B}\right) - h \tag{G3}$$

Total revenue:

$$TR = ph = pqBE \tag{G4}$$

Total cost:

$$TC = wE \tag{G5}$$

Total profit:

$$\pi = TR - TC$$

$$\Rightarrow \pi = (pqB - w)E \tag{G6}$$

Dynamic problem with continuous time:

$$\text{Max} \int_0^{\infty} e^{-\rho t}\left(pqB-w\right)E.dt \quad \text{subject to:} \qquad \begin{cases} \dfrac{dB}{dt} = rB\ln\left(\dfrac{K}{B}\right) - qEB \\ B(0) = B_0 \\ 0 \leq E(t) \leq E^{\max} \end{cases} \tag{G7}$$

Current-value Hamiltonian:

$$H(E,B) = (pqB-w)E + \mu\left[rB\ln\left(\frac{K}{B}\right) - qEB\right] \tag{G8}$$

The optimal biomass, effort and harvest are obtained using the following maximum principles:

$$\left.\begin{array}{ll} \text{(i)} & \dfrac{\partial H^c}{\partial E} = 0 \\ \text{(ii)} & \dfrac{\partial H^c}{\partial \mu} = \dot{B} \\ \text{(iii)} & \dot{\mu} - \rho\mu = -\dfrac{\partial H^c}{\partial B} \end{array}\right| \tag{G9}$$

Solving the maximum principle $\dfrac{\partial H^c}{\partial E} = 0$,

$$\Rightarrow pqB - w - \mu qB = 0$$

$$\Rightarrow \mu = \frac{pqB-w}{qB} = p - \frac{w}{qB} \tag{G10}$$

Solving the maximum principle $\dfrac{\partial H^c}{\partial \mu} = \dot{B}$,

$$\Rightarrow \dot{B} = \frac{dB}{dt} = rB\ln\left(\frac{K}{B}\right) - qEB \tag{G11}$$

At steady-state, $\dot{B} = 0$

$$\Rightarrow rB\ln\left(\frac{K}{B}\right) = qEB$$

$$\Rightarrow qE = r\ln\left(\frac{K}{B}\right) \tag{G12}$$

Solving maximum principle $\dot{\mu} - \rho\mu = -\frac{\partial H^c}{\partial B}$,

$$\Rightarrow \dot{\mu} - \rho\mu = -pqE - \mu\left[r\ln\left(\frac{K}{B}\right) - r - qE\right] \tag{G13}$$

Using Equation G12,

$$\Rightarrow \dot{\mu} - \rho\mu = -pqE - \mu[qE - r - qE]$$

$$\Rightarrow \dot{\mu} - \rho\mu = -pqE + \mu r$$

$$\Rightarrow \dot{\mu} - \rho\mu - \mu r = -pqE$$

$$\Rightarrow \dot{\mu} - \mu(\rho + r) = -pqE$$

At steady-state, $\dot{\mu} = 0$

$$\Rightarrow \mu = \left(\frac{pq}{\rho + r}\right)E \tag{G14}$$

Using Equation G10 and G14,

$$\Rightarrow \left(\frac{pq}{\rho + r}\right)E = p - \frac{w}{qB} \tag{G15}$$

$$\Rightarrow E_{dynamic\_MEY} = \left(\frac{\rho + r}{pq}\right)\left(p - \frac{w}{qB}\right) \tag{G16}$$

Rearranging Equation G15,

$$\Rightarrow \frac{w}{qB} = p - \left(\frac{pq}{\rho + r}\right)E$$

$$\Rightarrow B = \frac{w}{q}\left[\frac{1}{p - \left(\frac{pq}{\rho + r}\right)E}\right]$$

$$\Rightarrow B = \frac{w(\rho + r)}{q[p(\rho + r) - pqE]}$$

$$\Rightarrow B_{dynamic\_MEY} = \frac{w(\rho + r)}{pq[(\rho + r) - qE]} \tag{G17}$$

Substituting $B_{dynamic\_MEY} = \frac{w(\rho + r)}{pq[(\rho + r) - qE]}$ and $E_{dynamic\_MEY} = \left(\frac{\rho + r}{pq}\right)\left(p - \frac{w}{qB}\right)$ into Equation G2 $(h = qEB)$, the equilibrium harvest at dynamic MEY is obtained:

$$h_{dynamic\_MEY} = \frac{w(\rho + r)E}{p[(\rho + r) - qE]} \tag{G18}$$

So, the equilibrium biomass, effort and harvest at the dynamic MEY are:

Biomass: $$B_{dynamic\_MEY} = \frac{w(\rho + r)}{pq[(\rho + r) - qE]}$$

Effort: $$E_{dynamic\_MEY} = \left(\frac{\rho + r}{pq}\right)\left(p - \frac{w}{qB}\right)$$

Harvest: $$h_{dynamic\_MEY} = \frac{w(\rho + r)E}{p[(\rho + r) - qE]}$$

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Chapter 5

Command and control in marine fisheries management: evidence from Bangladesh

5.1 Introduction

The potential of the marine fisheries sector in Bangladesh is considerable in view of the country's 714 km coastline and the Exclusive Economic Zone (EEZ) of 166,000 square kms. The marine water extends beyond the continental shelf, measuring 200 nautical miles from the base line (10 fathoms) including rivers and estuaries (DoF 2011). Bangladesh industrial marine fisheries are a part of Eastern Indian Ocean. The Bay of Bengal in the Indian Ocean is recognized as one of the most poorly studied area in the world and the most commercial fish stocks of the Bay of Bengal are considered as overexploited and are, under threat. A recent study on Indian Ocean shows that 41 stocks or species groups out of 47 were determined moderate-full exploited to full-overexploited and at there is a little room for further expansion. The study suggested that a better control over growth in fishing fleet capacity and a sustainable fisheries management are needed (FAO 2006). The FAO (2006) study recognized that excess capacity of fishing fleet are the main cause of overfishing, degradation of marine fisheries resources, decline in food production and significant economic waste in the Indian Ocean.

In Bangladesh fish plays a major role in different ways, such as, animal protein demand, foreign exchange earnings and socioeconomic development of the rural poor by alleviating poverty through employment generation. It is estimated that demand for fish will grow by 4.1 percent from 2010 to 2020 (GoB 2010). Marine fisheries of Bangladesh constitute about 19 percent of total fish production (with a growth of 5.4 percent per annum). Industrial marine fishery contributed 7.10 percent of the total catch and the share of total catch of the industrial marine fisheries has been static more than two decades (FAO 2007). In recent years, fish exports have played a significant role in the export sector performance of Bangladesh. Bangladesh earns 4.76 per cent of its foreign exchange from fisheries and aquaculture exports (FAO 2006). Although the share of export earnings from the fisheries sector has declined from 7.57 per cent in 1993 to 4.9 per cent in 2007, the quantity of fish exported has more than doubled between 1993 (26,607 tonnes) and 2007 (73,704 tonnes) (DoF 2007). The total value of fisheries exports has increased from US$ 178.91 million in 1992 to US$ 515.3 million in 2007 (BB 2007). Production from the marine shrimp accounts for around 6.25 per cent of the total exportable production of Bangladesh (DoF 2006).

Fisheries resources from artisanal[63] fisheries are used for domestic consumption and from industrial[64] fisheries are used for export earnings. To promote exports and encourage investment in export oriented activities, the Government of Bangladesh took a number of initiatives for trade liberalization and trade promotion in the late 1980s and early 1990s. Industrial marine fisheries enjoy fiscal concessions and credit facilities including direct incentive such as, a value added tax refund from fuel subsequent to export and indirect incentives such as duty free imports of capital machinery and raw materials, fiscal incentives for export, income tax rebates, duty drawback facilities, speedy customs clearance and subsidized credit as a part of the trade liberalization and export orientation policy of Bangladesh.

Marine fisheries in Bangladesh are a common property resource, which are subject to possible overexploitation in the absence of efficient and effective management. Bangladesh has centralized fisheries management system under Department of Fisheries of the Ministry of Fisheries and Animal Resources with implementation of management through district and sub-district (upazilla) offices. Management tools those are used in industrial marine fisheries of Bangladesh are issuance of fishing licence; gear restrictions (mesh size, gear type); temporal restrictions (closed season, days of fishing); and spatial restrictions (marine protected area/ sanctuary). The industrial fishery of Bangladesh is managed by the Marine Fisheries Ordinance 1983 (GoB 1983a) and the Marine Fisheries Rules 1983 (GoB 1983b). The Marine Fisheries Ordinance 1983 (GoB 1983a) regulates the management, conservation and development of marine fisheries. The Marine Fisheries Rules 1983 (GoB 1983b) regulate the issuance and conditions of fishing licenses, license conditions, types of fishing gear, mesh size, fishing area and

[63] The *artisanal marine fishery* is a small scale onshore fishery and fishing occurs up to 40 meters depth with mechanized and non mechanized boats.
[64] The *industrial marine fishery* is a large scale offshore fishery and fishing occurs beyond 40 meters depth within the EEZ of Bangladesh with industrial vessels.

fishing days. Fisheries management in the industrial fishery in Bangladesh were introduced in 1983 and modified several times between 1983 and 2004 to protect both shrimp and fish stocks and to reduce sea water pollution (details in Table 5.1, Appendix H) .

A number of surveys have been conducted to assess the pelagic and demersal stock and the survey area was at 10 to 100 meters depth[65] within the EEZ of Bangladesh (MFD 2009). But, controversy remains about the extent of fish resources within the EEZ. There exists also controversy whether the marine fisheries are under or overexploited. Signals of overfishing and stock exhaustion were perceptible and being reported from artisanal capture fisheries (FAO 2006) rather the industrial trawl fisheries. No surveys have been done separately yet for artisanal and industrial fisheries. Some measures (such as, Alam & Thomson 2001 and World Bank 1991) have been taken based on a few reports and without research based evidence on industrial marine fishery in Bangladesh. Hence, this research estimates the impact of input control on vessels performance (Chapter 2) in term of technical efficiency and productivity; stock assessment (Chapter 3); and the economic efficiency (Chapter 4) of the Bangladesh's industrial marine fishery to find out whether the fishery is overcapitalized, whether stocks are biologically overexploited and whether the fishery is economically profitable.

Based on research output of three studies (Chapter 2, 3 and 4), this research gives an idea of the performance of the industrial marine fisheries of Bangladesh. The study in Chapter 2 shows that vessels are producing below the maximum level of output and are too small in their scale of operation. It also shows input control induces vessels operators to intensify usage of unregulated inputs. The study shows that the input control that is employed in industrial marine fisheries of Bangladesh fails to increase vessels efficiency and productivity.

The study in Chapter 3 shows that the shrimp stock of the industrial marine fisheries is over-exploited and the fall in catch per unit effort (CPUE) over time of the industrial marine shrimp fishery is due to the fall in stock size. On the other hand, the fish stock of the industrial marine fisheries is under-exploited and the fall in CPUE over time of the industrial marine fish fishery is due to inadequate knowledge and information on the availability of the sizes of different fish stocks and lack of technological developments

[65] Includes both artisanal and industrial fisheries.

for harvesting the new resources. The study also shows that to maintain steady-state equilibrium and adequate growth rate of both shrimp and fish, fishing patterns need to be modified.

The study in Chapter 4 shows that excessive use of efforts makes both shrimp and fish fisheries economically inefficient in the form of low stock biomass and profit. The study also shows that reductions in the number of vessels in both shrimp and fish fleets are needed. The study indicates that the MEY is the best management target compare to the MSY to improve the economic efficiency of both industrial marine shrimp and fish fisheries of Bangladesh. Based on the findings of these three studies, this research confirms that in the absence of correct management targets and property rights, the open access Bangladesh industrial marine fisheries becomes inefficient and overcapitalized. The fishery also suffers overcapacity and is economically unprofitable.

The objective of this Chapter is to discuss the impact of traditional ‘command and control’ approach to reduce overcapacity and overexploitation in marine fisheries management with an evidence of industrial marine fishery of Bangladesh. The remainder of this Chapter is divided into three sections. Section 5.2 describes the causes of overfishing and overcapacity in fisheries management. Section 5.3 presents the traditional ‘command and control’ approaches to fisheries management with an evidence of Bangladesh. Section 5.4 concludes the Chapter.

5.2 Causes of overfishing and overcapacity in fisheries management

The mismanagement of natural resources increases widespread concerns in recent years over loss of biodiversity (e.g., Fisher 1988); overconsumption of the natural capital stock (e.g., Dasgupta 1990) and overexploitation of renewable resources (e.g., Sandal & Steinshamn 1996). The management of natural resource involves many factors such as, lack of well-defined property rights (Scott 1985), market failures (e.g., Panayotoy 1993), subsidies for exploiting the natural capital stock (e.g., Feder 1977) and inadequate consideration of future generations (e.g., Howarth & Norgaard 1995). FAO (2002) indicates that one of the important causes of the failure of the fisheries management is absence of clear and precise objectives[66] and hence the problems of overcapacity and overfishing have become key issues for fisheries management (FAO 2004).

Fisheries are common-pool resources[67] and the 'tragedy of commons' or lack of property rights (Hardin 1968) have been viewed as the underlying cause of overfishing; even lead to extinction of fish species. The property rights to resource are often unclear and access to resources is unrestricted (e.g., Grimble & Wellard 1997) and the property rights to the common resources arise when the benefits of defending claims to a resource exceed the cost of doing so (Hannesson 2010). The common property or 'common pool' (Ostrom 1990) of the nature of the resource promotes overcapacity (e.g., Parsons 2010), which is widely recognized as a major problem affecting world fisheries and can lead to the erosion of management control (Beddington et al 2007); causes severe stock depletion (e.g., Bjorndal & Conard 1987) and overexploitation (e.g., Gordon 1954; Hardin 1968; Clark 1990) and has resulted in the collapse of important fish stocks such as, Canada's northern Atlantic cod (*Gadhus morhua*) fishery (e.g., Hutchings & Myers 1994). Stock collapses (such as, northern cod fishery in Newfoundland and Labrador) are the most extreme example of management mistakes (Grafton et al 2006) or mismanagement (Moxens 1998) or management failure (Townsend 2010); and caused from incorrect economic incentives (e.g., Buchanan & Tullock 1962) or incentives for rent seeking (Kreuger 1974; Tullock 1967; Townsend 2010) or lack of appropriate incentives and institutions (that encourage fishers to behave in a sustainable way) limit the improvements in achieving economic efficiency. In the absence of incentives to fishers, the lack of property right leads to a build up of capital and excess capacity.

[66] Fisheries management depends on four goals: biological, economic, ecological and social. Biological goals maintain the target species at or above the levels to ensure their continued productivity. Economic goals maximize the net profit of the fishers involve in the fishery. Ecological goals minimize the impacts of fishing on the physical environment and on the non-target (by-catch), associated and dependent species. Social goals include political and cultural goals. Social goals maximize employment opportunities for those dependent on the fishery for their livelihoods (FAO 2004).

[67] Common pool resources have two distinct features- the catches are rivalrous, where fishing by one person reduces the catch available to others; and common pool resources are costly to effectively control the access and the harvest from them (Grafton et al 2004).

In open access[68] fisheries resources use, the existence of market failure (Hartwick & Olewiler 1998) and the 'race-to-fish' increases the number of fishers and vessels; and can lead to stocks depletion, fall in catch per unit effort (CPUE), decline in incomes and overcapitalization (Gordon 1954; Scott 1955). In common-pool resources, it is difficult to monitor the fishers and to enforce the regulation. To achieve sustainable use of renewable resource management actions are necessary (Heino 1997) and open access/common-pool cannot achieve an efficient allocation of resource without some form of government intervention, the creation of private property rights or both (Hartwick & Olewiler 1998). For an example, the common property problem in many fisheries requires right to harvest a specified amount of fish (e.g., Walden et al 2010). Most common form of property rights or right-based management is individual transferrable quotas (e.g., Hannesson 2004) which can motivate fishers as owners, to make production decisions that are not dominated by the imperative race-to-fish (Libecap 2010).

However, many open accesses or common-pool resources are in danger of being exhausted even with various types of government regulation such as, traditional 'command and control' approaches to fisheries management. Many regulations have not been successful due to putting 'fishers before fish', which has contributed to the problems of overfishing (Larkin 1978). Munro & Scott (1985) argue that unlike other renewable resources, the common property fishery resources are difficult to manage effectively. Because, fisheries management needs to put emphasis on many issues (eg., Hilborn & Walters 1992; Stephenson & Lane 1995), such as stock assessment, information on fishing capacity, behavior of fishing industries, constraints of harvesting, institutional capability, alternative uses, environmental impacts and so forth. On the other hand, the success of a management system is often defined in terms of biological, economic, social and political objectives. It is argued that while a stock is in such a depleted state that the long-term sustainability of the fishery is threatened- economic and social objectives will not be met. At the same time, without consideration being given to economic and social objectives- biological objectives are unlikely to be met (Beddington et al 2007). Argument shows that the fisheries management regime goal must be to reduce overinvestment in fishing and improve both conservation and

[68] Open access natural resources include many fisheries and environmental resources, such as, air and water. Fisheries and environmental resources have remained as open access for long period of times (Hartwick & Olewiler 1998).

economic/ social outcome (Ridgeway & Schmidt 2010) and a governance framework aligns with incentives can coherently deliver responsible outcomes of sustainable use of marine resources (Ridgeway & Rice 2010). Kompas et al (2009) argue that in the absence of correct management targets inefficient fisheries suffer overcapacity and low profits; and hence fisheries become both biologically over-exploited and economically unprofitable.

In an open-access fishery, subsidies[69] can exacerbate the common-property, or, 'common-pool' problems (FAO 2000; Munro & Sumaila 2002; OECD 2000) that is, subsidizing fisheries is the cause of overcapacity and overexploitation of fish stocks (e.g., Beddington et al 2007; Cox & Sumaila 2010; Munro & Sumaila 2002; Willmann & Kelleher 2010). Subsidies combined with rapid technological advancement encourage a 'race-to-fish', with consequent adverse impacts on fish stocks and often deplete stocks below the minimum biological reference point (Grafton et al 2010). Subsidies in fisheries reduce the cost of harvest (eg. through vessel construction subsidies or fuel tax exemptions) which encourages further vessels to enter into the fishery (direct affect on the fishing capacity) and hence considered as the cause of dissipation of economic rent (e.g., Cox & Sumaila 2010; Hannesson 2001; OECD 2006; Willmann & Kelleher 2010). It is argued that depending on the fisheries management regime (whether open access or controlled by property rights) and the state of the fish stock (whether above or below maximum sustainable yield) (Hannesson 2001; OECD 2006; Porter 2002; Cox & Sumaila 2010), subsidies have different impacts on the economic and resource effects and the impacts depend critically on the effectiveness with which management regulations are enforced. The issue of subsidies is closely related to the fiscal policies[70] for fisheries and also related to the weak property rights in most fisheries which directly undermine the sustainability of fisheries because they lead to a bio-economic equilibrium with high levels of fishing and low stock size (Beddington et al 2007).

[69] "….Common fisheries sector subsidies include grants, concessional credit and insurance, tax exemptions, fuel price support (or fuel tax exemption), direct payments to industry (eg, vessel buyback schemes), fish price support, and public financing of fisheries access agreements…..Policy changes such as relaxation of environmental regulations governing fisheries, or special work permits for migrant fish-workers (crew) can also reduce costs in the sector, and such distortions have also been regarded as a form of subsidy" (Willmann & Kelleher 2010).

[70] "…Fisheries subsidy have been provided for a wide range of purpose, including stimulating industry development, supporting regional communities, providing fisheries infrastructure and support services, retiring fishing capacity and supporting early retirement for fishers" (Cox & Sumaila 2010).

5.3 'Command and control' approaches in fisheries management

To address overcapacity and overexploitation of common pool marine capture fisheries resource, traditional 'command and control' approaches and 'right-based' approaches are mainly used as fisheries management tools. The traditional 'command and control' and 'right-based' approaches are often known as 'incentive blocking measures' and 'incentive adjusting measures', respectively (FAO 2004). This Section focuses on the 'command and control' approaches that often results in unforeseen and undesirable consequences (Holling & Mefe 1995).

Traditional 'command and control' approaches involve mainly output or harvest control, limited entry and input control. Output or harvest controls are used to maintain or rebuild fish stocks by establishing a total allowable catch (TAC) (FAO 2004) that helps to decide how the annual catches from a fish stock should be adjusted in response to stock size to achieve sustainability and other objectives set by the management (Hilborn & Walters 1992), but, TACs have not proved effective or precautionary in preventing stock depletion (Caddy 1999). Many TAC regulated fisheries have experienced an unexpected increase in fishing capacity, as additional vessels enter the fishery in response to (temporarily) positive rents. TACs would maintain a stock level well above that of bio-economic equilibrium, if the TAC is correctly specified and enforced. TACs also encourage 'race-to-fish', overcapitalisation in terms of both investments on board and fishing capacity, for example, Italian fisheries (Spagnolo 2010); illegal-unregulated-unreported (IUU) fishing, for example, Eastern Baltic cod fishery (Beddington et al 2007). On the other hand, harvest control strategies have to cope with fluctuations in the stock size, with inherent inaccuracy of the estimates of stock size (Ludwig et al 1993; Walters & Maguire 1996) and must take into account economical, political, and social consequences (Hilborn & Walters 1992).

The limited-entry (such as, issuing fishing license) is used in many fisheries like, Bangladesh industrial marine fisheries, to address the open-access problem by restricting entry of fishing vessels to the fishery. It is argued that limited entry licensing is not a sufficient measure to address overcapacity and overinvestment[71] (Parsons 1993), because it gives a privilege of fishing, but, doesn't confer property rights to the fisher (Parsons 2010). In many fisheries, for example, the Pacific salmon limited-entry licensing program has been considered as unsuccessful (e.g., Fraser 1979; Pearse 1982) though the experience in the Atlantic lobster fishery shows a positive outcome (Parsons 2010). On the other hand, limited license buybacks schemes are considered a key policy tool to address overcapacity, overexploitation of fish stocks and distributional issues in fisheries (Holland et al 1999) and have been tried in various fisheries such as, Japan, the United States, Canada, Norway, Australia, European Union, and Taiwan (FAO 2004). However, buyback generate changes in vessel-level behaviour, both intended and unintended and do not resolve 'race-to-fish' incentives created by incomplete use or property rights, inadequate governance, and uncertainty (Squires et al 2010) and have not been successful in reducing overcapacity (Holland et al 1999).

Input controls, includes restriction on mesh size, gear type and vessel length; temporal restrictions (such as: closed season, days of fishing) and spatial restrictions (such as: closed area), are used to control overcapacity and overexploitation of the marine fisheries resources. Many countries introduce input controls (Caddy 1999), but, fails to provide the incentives to vessel owners. Input control measures often increases substitution from regulated to unregulated inputs (Wilen 1979) and result in 'effort-creep' and 'excessive and wasteful competition' (Kompas 2005; Kompas et al 2009) in many fisheries, for example, Bangladesh industrial marine fisheries. The study on impact of input control on vessels' performances (in term of technical efficiency and productivity) of the industrial marine fisheries of Bangladesh in Chapter 2 shows input control induces vessels operators to intensify usage of unregulated inputs. Input controls also have a negative impact on technical efficiency and thus cost and profitability in a fishery (e.g., Greenville et al 2006; Kompas et al 2004; Pascoe & Robinson 1998), except the situation when the unrestricted inputs are poor substitutes for the restricted inputs (Anderson 1985; Campbell & Linder 1990; Townsend 1990). The study in Chapter 2 also shows that the input control that is employed in industrial marine fisheries in Bangladesh fails to increase vessels efficiency and productivity. The study shows that vessels in Bangladesh are producing below the maximum level of output and are too small in their scale of operation. However, in general, input control measures

[71] Increase in vessel's horsepower, length, breadth, and tonnage; changes in gear; changes in fishing periods or areas; and the adoption of technological innovations in fishing gear (FAO 2004).

are not successful due to two reasons (Townsend 1990). First, controls on one or more inputs provide an incentive to substitute uncontrolled inputs and hence results in ‘effort-creep’. Second, input control regime provide a very little sense of ownership such as, the right of access to the fishery under certain guidelines which encouraged ‘race-to fish’ within those rules (Grafton et al 2006; Kompas 2005; Kompas & Gooday 2007; Townsend 1990).

However, a ‘command-and-control’ approach is considered as most inappropriate approach to reduce overcapacity and overexploitation (e.g., Spagnolo 2010). For example, the findings in Chapter 2, 3 and 4 of this research confirm that the ‘command and control’ approaches to the industrial marine fisheries management of Bangladesh fails to increase efficiency and to control overcapitalization; the fishery suffers overcapacity and the fishery is economically unprofitable. The findings also confirm that the industrial marine shrimp fishery is biologically overexploited.

5.4 Conclusion

A ‘laissez-faire’ approach to fisheries doesn’t work to address ‘tragedy of commons’ and ‘failures associated with open access fishery’ (Grafton et al 2006). In the long run, ‘command and control’ approach cannot prevent economic overfishing, and fail to maximize economic profit and hence economic efficiency in the fishery. So, an economic perspective of fisheries management is necessary, which shows marine resources should be managed sustainably so that they can contribute to and provide net benefit for the nation as a whole. Thus, an economically viable fishery can be an ecologically sustainable fishery.

Given the problems of the open access market failures and the absence of well-defined property rights (Grimble & Wellard 1997; Hartwick & Olewiler 1998; Perman et al 2011), fisheries to be economically efficient requires correct management targets. Correct and effective management targets are important to achieve maximum economic efficiency from a fishery. Maximizing economic efficiency in fisheries requires setting appropriate level of catch and effort levels and MEY gives the maximum economic efficiency of fishers and shows no overcapitalization of vessels or gears. Effective management of fishery requires an understanding of how the fishery system is performing relative to reference points (Beddington et al 2007). MSY is not a safe target for management (Larkin 1977; Sissenwine 1978; Caddy 1999), while MEY is considered as more 'conservationist' than MSY as the equilibrium stock at the MEY is larger than at the MSY and larger stocks helps protecting the fishery from unforeseen or negative environmental shocks (Kompas et al 2009).

Efficiency and productivity measures are also important to hold the MEY levels. Efficiency analysis shows the factors those are affecting the economic performance of the fishery and the impacts of fisheries regulations. Productivity measures also indicate the ratio of output to inputs and provide a benchmark of vessels performance. If an effective management structure wants to prevent biological and economic overexploitation, improvements of efficiency by vessels are desirable. Changes in efficiency of vessels are also strongly influenced by regulations. Imposing restrictions on what gear can be used by fishers affects the ability of vessels to harvest fish, and thus their efficiency. Efficiency in fisheries is not possible without relating it to governance and management (Grafton et al 2006). To maximize vessels efficiency vessels must use right amount and combination of inputs to minimize the cost of harvest at the MEY level. This require fishery control instruments to encourage autonomous adjustment and to allow vessel owners to freely combine inputs, such as, gear, engine size, crew in proportion to minimize costs. On the other hand, to remove the incentive for a wasteful and inefficient 'race- to- fish' by the vessel owners, effective property rights are also important. So, for an efficient and effective fisheries management, adopting the right target level of effort that maximizes profits regardless changes in prices of harvest and the cost of fishing; and using an instrument that protects the future of the fishery to achieving the target are considered as the solution (Kompas et al 2009).

In the absence of correct management targets, inefficient fisheries suffer overcapacity/excess fishing capacity and low profits and hence fisheries become both biologically over-exploited and economically unprofitable. Bangladesh industrial marine shrimp and fish fisheries are the examples of such inefficient fisheries. The findings of three studies in Chapter 2, 3 and 4 of this research confirms that in the absence of correct management targets and property rights, the open-access Bangladesh industrial marine fishery becomes inefficient and overcapitalized. The fishery also suffers overcapacity and the fishery is economically unprofitable. This research also confirms that the industrial shrimp fishery is biologically overexploited.

Fisheries legislation in Bangladesh is too old and policies are more focused on increased production with little emphasis on conservation or sustainable fisheries management. A reform in legislation and management system of the industrial marine fisheries of Bangladesh is needed. To protect economic and biological overfishing a correct management target and 'right-based' that is an incentive adjusting approach is needed so that the fishery could be both economically profitable and biologically sustainable.

Appendix H

Table 5.1 **Change in industrial marine fisheries management over time**

Year	Description
1983	Marine fisheries management introduced Marine Fisheries Rules 1983 Marine Fisheries Ordinance 1983 (Ordinance no. XXXV) Identification of marine fisheries: artisanal fisheries (within 40 metres depth) and industrial fisheries (beyond 40 metres depth)
1985	Formation of Zaman Committee to assess the provisions of the Marine Fisheries Ordinance 1983 Recommendation for no new entry into the fisheries until stock assessment will be done Number of total vessels 73 (Shrimp: 28; Fish: 45) Restriction on bycatch Mesh size restriction: 45mm for shrimp trawl net and 60mm for fish trawl net
1987	FAO Survey findings: opportunity to introduce perse seiner, long liner and mid-water trawling and estimated MSY: 47, 500 metric tonnes for pelagic and meso-pelagic species
1990	Trawling is categorized as Industry Board of Investment: authority of vessel registration
1993	Modification on bycatch restriction
1994	Government decision for restriction on new entry Sailing permission: 30 days per trip for freezer vessel and 15 days per trip non-freezer vessels One month (15 January- 15 February) season closure for the shrimp fishery
1996	Formation of Task Force to classify the vessels Recommendation of the Task Force: no new entry into the shrimp fishery and new entry into the fish fishery Ministry of Fisheries and Livestock: authority of fishing license
1997	Inter-Ministerial Meeting Decision of the meeting: 'first come first serve' basis open access trawling for both shrimp and fish fisheries Suggestion for stock assessment 2nd Inter-Ministerial Meeting Suggestion for a formation of technical committee to assess the potential and problems of marine and coastal fisheries Formation of Karim Committee for examining the potential and problems of marine and coastal fisheries Recommendation for 40 vessels, for new entry into the fisheries for harvesting pelagic and meso-pelagic species
1998	Formation of a Committee to assess the number of vessels 68 vessels (49 shrimp vessels and 19 fish vessels) are engaged in fishing Suggestion for not to increase number of vessels until stock assessment will be done Marine fisheries management policy in National Fisheries Policy

Continued…..

Year	Description
2000	Government decision for restriction on new entry Entry of 10 new vessels by the order of High Court Identification of 4 fishing grounds Declaration of 698 square km marine reserve and two marine sanctuaries
2001	Entry of 5 new vessels by the order of High Court
2002	Entry of 3 new vessels by the order of High Court Total vessels 102 (55 shrimp vessels and 47 fish vessels)
2003	Shrimp vessels will be replaced by fish vessels after the end of shrimp vessels life Restriction on import and construction of new shrimp vessel Maximum 4 vessels per owner/company Minimum fishing days: 150 days per year per vessel Entry of new vessels by the order of High Court
2004	Restriction 'no discard' Entry of new fish vessels
2006	Marine fisheries management strategy in National Fisheries Strategy
2009	Total vessels 146 (116 license from Ministry of Fisheries and Livestock and 30 by the order of High Court)
2010	Marine fisheries management in Perspective Plan 2010-21
2011	Marine fisheries management in Sixth Five Year Plan 2011-15 Total 243 (133 from Board of Investment and Ministry of Fisheries and Animal Resources, and 110 by High Court order) permitted vessels and among them 170 vessels engaged in fishing

Source: Ministry of Fisheries and Livestock 2009, 'Unpublished official records', Dhaka.
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DOF, see Department of Fishery

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