Matters of Management, Sustainability, and Efficiency: Essays in Fisheries

By

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THESIS

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Declaration

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Abstract

This thesis addresses three main issues in fisheries management: monitoring and enforcement; profit efficiency; and factors determining profit efficiency. The overall objective is to provide broad theoretical and empirical analysis of fisheries management issues that seek to address sustainability and efficiency questions in the industry.

The first issue investigated is whether monitoring and enforcement, as management policy instruments, can lower illegal harvesting and therefore preserve fish stocks. Using a game theoretic approach the strategic interaction between management and fishers, in the presence of illegal, unreported, and unregulated (IUU), is examined. Results of the analysis show that equilibrium compliance strategies of fishers affect stocks over time. It is further observed that increasing the cost of engaging in illegal activities, through punishment, may be sound economic policy.

The second issue examined is efficiency in the South Australian Rock Lobster Fishery. To do this a new approach, in the context of fisheries, is used to overcome the small sample sizes and negative profit challenges inherent in fisheries. Specifically, the Nerlovian and Directional Distance Function methods are used to decompose profits of the fisheries into technical and allocative efficiencies. In addition, the meta-frontier efficiency technique is used to compare the Northern and Southern Zones, the two fisheries in the South Australian Rock Lobster Fishery. Results show that profit inefficiency in this fishery can be largely attributed to allocative inefficiency. Further, it is observed that there is significant variability between efficiency levels in the Northern and Southern Zones.

The final issue considered is the natural question of what factors, besides technical and allocative inefficiency, may possibly explain profit inefficiencies in the South Australian Rock Lobster Fishery. To answer this question we investigate the effects of incorporating a fixed input on equilibrium profits and biomass. We first set up a theoretical model with an input that is fixed in the short-run (vessel size) but that can be used with a variable input at sub-optimal capacity. We use this model to get predictions for the impact on profits of exogenous changes in biomass, output price and vessel size. These give us interesting theoretical insights into why it is important to incorporate fixed inputs into profit analysis. We then conduct an empirical investigation to gain an understanding of the effects of these non-discretionary
factors on profit efficiency. In particular, we apply a truncated regression with bootstrap methodology to data on individual firm profit efficiency from the South Australian Rock Lobster Fishery. We find empirical support for our predictions that increased biomass and smaller vessel length are associated with higher profits. An additional empirical result is that individual quota management is positively associated with profit efficiency.
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Dedication.

To Sylvia, Nana, and Maame.

You gave me your support and encouragement, you endured my long absence, and you gave me your love unreservedly.

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Ma, your memory is forever cherished.
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Chapter 1

Introduction

The ocean is a major hub of economic activity for the world and indeed for Australia. Over several centuries fish have been important to the world economy, and currently provide about 16 percent of the total world protein with higher percentages occurring in developing nations (Laurenti, 2008). Australian fisheries are a major source of revenue, with commercial, recreational, and subsistence fisheries bringing in millions of tons of fish, providing food and livelihood, worth millions of dollars annually to coastal communities (FAO, 2002). The South Australian Rock Lobster Fishery in 2008/09 for example: had catch value of $105 million; contributed nearly 41% of all fisheries’ contribution to South Australia’s gross state product; and 36% employment, and 39% of household income in the state’s fishery sector. Economic and biological sustainability of the fishery is, therefore, important to both managers and firms in the sector. Pauly et al. (1998) provide evidence of changes in fish species trophic levels, and emphasise that present trends in decline in trophic levels of fisheries landings is likely to lead to widespread fisheries collapse. It is therefore necessary to manage fisheries to ensure optimal use of this valuable resource.

The sustainability concern has been re-emphasised by the Food and Agricultural Organisation of the United Nations (FAO). According to FAO (2009), most of the
stocks of the top ten species, which account in total for about 30 percent of the world marine capture fisheries production in terms of quantity, are fully exploited or over-exploited and, therefore, cannot be expected to produce major increases in catches. Similar concerns have been raised by Pauly et al. (1998) in the past. In addressing the issue of uncertainty in fisheries Munro (1992) points out that the problem of resource uncertainty requires that effort must be made to control fishing effort, and consequently harvest, in order to ensure some form of conservation and sustainability. He maintains that an important consequence of resource uncertainty is to lead to the prescription of a more conservationist management policy.

A number of issues currently confront fisheries management around the globe. Among these are: illegal, unregulated and unreported (IUU) fishing activities and the attendant management challenges; the impact of IUU on fish stocks; and issues of efficiency and sustainability of the industry across time. Destructive and illegal fishing activities, among other things, include unauthorized by-catch, discard, exceeding allowable quotas, the use of explosives, and the use of unauthorized fishing equipment. These activities not only violate fisheries regulatory measures but also undermine management programmes and affect fish habitat, and are therefore considered a major threat to sustainability of fisheries resource and its ecosystem. Illegal activities are common and sometimes reach extreme proportions (Clark, 1985), and have become a global concern in recent years (FAO, 2002).

In fisheries a major interest to policy makers is the sustainability of the industry. This means that a critical evaluation of factors affecting efficiency in the industry is vital for sound policy formulation aimed at ensuring the industry’s sustainability across time. In addition to the need to identify sources of suboptimal use of the resource, issues of efficiency are also of major interest to managers, firm owners and other stakeholders in the fisheries industry. In the past efficiency studies in fisheries
have focused on productivity, technical, cost, and in some instances, revenue and profit analysis. Attention to profit efficiency analysis has been minimal compared to others. Profit efficiency in itself is one of the major factors that can help explain firm survival and growth, as well as changes in industry structure.

To address the challenges facing the industry it is important to be able to estimate the impacts of various fishery management policies, as well as the consequences of fishing practices in the industry, on fish stocks. This calls for policies and practices that can effectively address marine conservation issues including overfishing and sustainability of the fisheries, ensure profitability in the sector, free resources to other sectors of the economy when necessary, and optimize the use of fisheries resources. Policy makers and individual economic agents value information on the likely impact of fishing activities and management strategies. There is demand for economic models that better estimate the economic impacts attributable to policies and practices. This thesis takes advantage of new techniques that overcome existing empirical challenges and applies innovative theoretical methods to examine fisheries management, sustainability and efficiency questions.

Current literature on marine resources, including fishery, focuses on varying aspects of the subject including but not limited to, conservation and preservation methods; and methods that ensure economic efficiency, including management regime types, and challenges. However, while various measures have been taken to address the above issues, concerns remain about the outcomes. The search for answers and solutions is an ongoing exercise. The focus of this thesis is the relationship between IUU and fish stocks, management policy challenges, profitability, and sustainability of the fishery industry. Explored here are the links from policy changes to the size of the fish stock. This analysis is based on examination of the way that profit-seeking fishers respond to policy and regulation, via their interaction with policy makers,
and how the decisions of both parties affect fish stocks. The theoretical analysis assumes all firms are the same and that they all maximise profits. In fact, we find variation in profits among fishing firms, so also examined is the profit performance of firms in fisheries of different characteristics.

Fisheries management involves a complex balance between ecological and stock sustainability, economic performance and community benefit (Haward et al., 2000). Sustainability concerns in Australia continue to engage the attention of policy-makers, managers and fishers alike. For example, it is observed that the growth and viability of Australian abalone is intrinsically linked to the need to protect the environment; protecting the wild stock in surrounding waters to ensure their sustainability (Shepherd and Partington, 1995). Kompas et al. (2009) rightly point out that sustainability remains a great concern to both fishers and managers alike. Sustainability from a business and community point of view depends not only on the size of the stock but also on the profitability of the operations of the fishery. Data from the South Australian Rock Lobster Fishery are used for this empirical work in the thesis. This leads to examination of a link in the other direction, from stocks back to profitability. This relationship depends on a number of other variables, including policy, which must be isolated in order to identify the relationship of interest.

The problem of overfishing leaving stocks at levels less than optimal is a familiar theme in the fisheries literature (Conrad, 2010). Previous work on the design of policy responses has failed to take account of the interaction between fisheries managers and fishers in the application of policy.\(^1\) Chapter 3 of of this thesis uses game theoretic concepts developed by Harrington (1988) to shed light on the consequences of strategic interactions between fishers and managers of fisheries in

\(^1\)For example, Charles et al. (1999); Gibson et al. (2005); Coelho et al. (2008), suggest that theoretical investigation of monitoring and enforcement in fisheries management remains uncommon.
the presence of illegal, unreported, and unregulated (IUU) fishing. Modeling this as a two-person dynamic game gives rise to steady-state equilibrium in which the optimal enforcement strategy of the fisheries manager is less than perfect in response to fishers’ compliance and violation behaviour. We show that a combination of fines, inspections and group classification (that is, group 1 or group 2), if properly applied, are important instruments that may help reduce the negative impact of illegal effort on fish stocks. In particular, it is revealed that even using less than perfect monitoring and enforcement can lower illegal harvesting, which is beneficial for stocks. Fishers’ illegal activities have been shown here to place less value on the future of fisheries by using discount factor higher than that which will ensure sustainable harvest over time. Our results also indicate that contrary to empirical evidence suggesting increasing maximum penalties considerably (Ostrom, 1990), punishment should have an upper bound if it is to achieve its intended purpose. This is because when punishment exceeds marginal gains illegal effort increases, with the attendant negative effect on stocks.

The second major fisheries issue addressed in this thesis is the issue of efficiency. In the past, efficiency analysis in the fisheries literature has mainly focused on productivity, cost and revenue, with relatively few investigating profit efficiency. For example, Fox et al. (2003) and Dupont et al. (2005) examine profit efficiency using index numbers; Sharp et al. (2004) investigate efficiency gains within rights based governance system. Previously constraints on the ability to focus on profit efficiency were small sample sizes and observations of negative values for profits, which complicated the statistical analysis. Chapter 4 considers a new approach, in the context of fisheries, to overcome these challenges, inherent in fisheries, to examine profit efficiency in the Northern and Southern zones of the South Australian Rock Lobster Fishery. As a first step, we decompose profit efficiency of the rock lobster fisheries into technical and allocative efficiencies. This is interesting because
we are able to tease out other components of profit efficiency, and therefore able to provide adequate information for managers and policy makers alike. We then use meta-frontier efficiency techniques to compare the Northern and Southern Zone fisheries.

This thesis is the first to apply these methods to examine profit efficiency of the South Australian Rock Lobster Fishery in order to investigate the economic performance of the fishery. The data used covers two management systems, total allowable catch (TAC) and individual transferable quotas (ITQ), thus making it possible to assess the effect on management system changes on profit efficiency in the fishery. We show that though operational cost in the Southern Zone is lower than in the Northern Zone, on average the Northern Zone is more profit efficient than the South. This is not unusual. Berger and Mester (1997) suggest that a firm’s cost efficiency levels may not necessarily explain its performance in terms of its profit efficiency. Examining cost and profit efficiencies in banks Berger and Mester (1997) found that measures of profit efficiency are not positively correlated with cost efficiency. They indicate that each corresponds to how well a firm performs relative to a different economic optimization program, and that each may provide different insights about firm efficiency.

An interesting component of the profit efficiency investigation is the critical evaluation of factors affecting profit efficiency that are not directly considered in the computation of the efficiency measures. These include non-discretionary factors such as the biomass, boat age, boat length, market shock, and others. Identifying the effect of such factors on profit efficiency is vital for sound policy formulation aimed at ensuring the industry’s sustainability across time. The thesis argues that in fisheries a major interest to policy makers is the sustainability of the industry. Chapter 5 therefore carries out this evaluation with two main objectives.
The first of these objectives is to provide a theoretical basis to justify the need to consider the importance of vessel capital when evaluating profit efficiency in fisheries. We first argue for a modified version of fixed cost in the investigation of profit maximization in fisheries. We then carry out a theoretical examination of the effect of fixed capital, in the firm’s profit maximization, on fish biomass across time. We do this with a focus on total allowable catch (TAC), and individual transferable quota (ITQ) management regimes. TAC is generally set by fisheries management, on season-by-season basis, based on biological estimates from marine biologists. ITQ is rights based TAC management system, allocated to individual registered fishers. Based on the heavy initial capital outlay, fixed cost is considered important in fisheries (Clark et al., 1979). For example, empirical evidence suggests that vessel size does matter in efficiency measures when quota system is introduced. Both large and smaller vessels are affected differently for various reasons (Grafton et al., 2006). For example, analysing the impact of input control on technical efficiency in a fishery, Kompas et al. (2004) show that technical efficiency depends positively on a measure of vessel size and engine power that is used to control fishing effort. This underscores the need to separate costs directly associated with fishing vessel from other operating costs. The second is to identify factors beyond firms’ control which can significantly affect profit efficiency. To achieve this objective we empirically analyse the possible effect of non-discretionary factors on profit efficiency of the South Australian Rock lobster Fishery, using truncated regression with bootstrapping. The results provide interesting theoretical and empirical insights into why fixed cost and non-discretionary factors are important in profit analysis in fisheries, in both the short and long runs.
Summary

The overall purpose of this thesis is to: provide further insights on issues confronting the future of the fishing industry; suggest possible management strategies given fisher behaviour; and draw attention to new methods, in the context of fisheries, which may alleviate some empirical examination challenges in the fisheries literature. A major contribution of the thesis to existing literature is the adoption of theories and techniques from economics and operations research to understand and offer insights into management and sustainability challenges in fisheries economics. For example, Chapter 3 applies game-theoretic concepts adopted from environmental economics literature to investigate illegal activities in fisheries. Chapters 4 and 5 adopt new techniques, in the context of fisheries, from operations research and econometrics to investigate firm economic performance and the possible underlying factors. These new techniques provide further evidence on what managers and policy makers should care about when considering policy options aimed at conserving the South Australian Rock Lobster Fishery. In this direction we consider our attempt a significant contribution to existing literature in the field.

The thesis begins with a review of literature to indicate the state of fisheries economic research on illegal fishing, profitability and sustainability. Chapter 3 focuses on the fisher-manager interaction in a dynamic game of fishers’ compliance and violation behaviour. The model gives rise to a steady-state equilibrium, characterizing the less-than-perfect enforcement strategy of the fisheries manager in response to the fishers’ behaviour. The chapter provides analysis of one of the key fisheries management challenges identified in Chapter 2. Chapter 4 carries out empirical analysis of profit efficiency in the South Australian Rock Lobster Fishery. Chapter 5 combines empirical and theoretical analysis to gauge out issues confronting the future of fisheries, using the South Australian Rock Lobster Fishery as a case.
Chapter 6 gives some concluding remarks as well as ideas for future work that will expand upon the potential of the methods employed in this thesis.
Chapter 2

Related Literature

We start with a general discussion of the fishery as an important natural capital stock in Section 2.1 and the need to preserve it to ensure growth and sustainability. This is followed in Section 2.2 by discussions of different management systems and the shortfalls of models assessing the success of these systems. In this Section we also discuss exploitation challenges and how these challenges affect the sustainability question. The illegal, unreported and unregulated problem is discussed in Section 2.3, with further emphasis on sustainability and property rights provided in Section 2.4. Issues of economic efficiency in the industry are reviewed in Section 2.5.

2.1 Fisheries as Natural Capital

Emphasizing the importance of marine resources, it is argued that ocean resources can provide the means for shifting the economy into a new and more favourable economic growth path (Arnason, 1993). This argument stresses views earlier expressed by Hardin (1968), and re-echoed in later works by Fox et al. (2003), Grafton et al. (2006), and McWhinnie (2009).
Clark and Munro (1975), hold the view that the economics of fishing, like other branches of natural resource economics, should ideally be cast in capital-theoretic terms. This means that, similar human decisions and actions aimed at accumulating physical capital can be taken to allow for future growth of the fishery resource. Clark (1990) also indicates that the resource stock as capital asset is as old as capital theory in itself. To emphasise these points Munro (1992) maintains that a fishery resource is a form of capital, yielding a stream of economic benefits to society through time. As a ‘natural capital’, Munro argues that a fishery resource can be built through investment, or disinvestment through depletion. This means the fisheries resource can be built up through conservation and postponement of current harvesting. Describing the capital theoretic aspects of fisheries Scott (1955) had earlier shown that a private owner who neglects the future productivity of the fish stock reaches the same stock level as the open access fishery. Another vital observation is that the importance of distinguishing between socio-economic processes leading to increased efficiency from capital investments lies in the different effects each of the processes has on sustainability of exploitation (Jul-Larsen, 2003).

**Preserving the Marine-Ecosystem**

It is noted that preserving the fish stock as a stream of wealth is based on the knowledge that fish stock can be classified as ‘living funds’ that produce for both humans and other marine organisms and, therefore, providing services to the marine environment. As ‘living funds’ fish not only sustains other marine organisms, but also yield a stream of economic benefits to society through time, as earlier noted. Managing fish stocks with an ecosystem-based approach is, therefore, likely to stop the divestment of the natural capital by combining sustainable use strategies with the preservation of marine ecosystems (Döring and Egelkraut, 2008).

In a study on the Baltic Sea Cod Fishery Döring and Egelkraut (2008), for example,
show that the use of more selective fishing methods can greatly lessen the impact on stock without loss of economic viability. It is further established that gains of such eco-premium reduce uncertainty thereby leading to drop in discount rates to levels comparable to other sectors of the economy, that is, the risk adjustment rate. There is the argument of the neglect of preservation of the marine ecosystem when addressing the sustainability problem of fisheries. For example, Döring and Egelkraut (2008) point out that management of the extraction of marine resource is usually based on maximizing the long-term consumptive yield of individual stocks to the neglect of their service function. Concerns over the need to preserve both marine habitat and biodiversity as possible means of addressing the sustainability question partly explain the increased attention marine reserves have received in recent years (Grafton et al., 2006). With respect to Australian fishery, Fletcher et al. (2005) maintain that ecological sustainable development is not limited to the management of the effects on target species but also the effects the fishery may have on the broader ecosystem - an environmental implication. For example, it is observed that the growth and viability of Australian abalone is intrinsically linked to the need to protect the environment; protecting the wild stock in surrounding waters to ensure their sustainability (Uglem et al., 2008). In order to preserve the ecosystem, reduce uncertainty, and promote investment, in the fish stock, management and policy makers need to institute measures that discourage undesirable fishing practices. It should also be noted that fisheries management involves a complex balance between ecological sustainability, economic performance, and community benefit (Haward et al., 2000).
2.2 Management Systems

Various analyses of the ‘Tragedy of the Commons’ in marine resource management, including Gordon (1954) and Hardin (1968), have resulted in the suggestion and trial of different management options in the fishing industry across the globe. The use of incentive mechanisms to achieve biological, as well as economic outcomes is considered to hold more promise for the future. A number of management options are currently in use in different fisheries around the world. For example, in recent years some prominent fishing nations, including Australia, New Zealand, Canada and Iceland, have adopted advanced versions of individual transferable quota (ITQ) systems in their fisheries (Arnason, 1993). The primary motivation for these management options is the need to address sustainability concerns and manage fisheries in a way that fisheries resources will be preserved, and economic efficiency of the industry maximised. To achieve these objectives governments identify the ITQ system as their preferred method (Arnason, 1993).

Searching for Optimal Biological and Economic Outcomes – A Management challenge

Management regimes in fisheries range from open access (common property); total allowable catch (TAC) without fishing rights; TAC with fishing rights allocated to a number of fishers (limited licenses); TAC with fixed percentage shares (property rights as allocation of catch shares, also known as fishing quota or individual quota, IQ); and, individual transferable quotas (ITQs), with full property rights. IQ or IFQ (individual fishing quota) gives property rights in a given fishing period. This is neither a permanent ownership nor transferable right and may be lost upon leaving the industry. IFQ, unlike ITQ, falls short of providing full property rights. ITQ owners have full property rights to fixed shares of the fishery, with transferable
rights. The main distinction between IQ and ITQ is the transferability element (Nowlis and Van Benthem, 2012)

Open access has been found to lead to over exploitation of the stocks, leading to possible collapse or extinction of some species (Clark, 1973). TAC, without allocation among fishers (no property right), if not properly monitored with full enforcement may lead to overcapacity with negative consequences on profits and stock. TAC regimes with limited licenses is equally found to result in ‘Olympic’ fishing with the attendant adverse effect on stocks. IQ though is meant to address the ‘race-to-fish’ phenomenon and overcapacity issues, lack of incentives could compromise stock levels even under this regime. Besides other reasons, detailed later, fishers or fishing firms planning to retire or go out of business may be motivated to engage in illegal fishing activities. In other words, since IQ does not offer its holders transferable rights these owners may not have the incentive to conserve the stock for the future. Arnason (1990) and Grafton (1996) argue that when fishers do not view their quota as exclusive and permanent harvesting rights they face short-term incentives, thus removing the uniform incentive among participants and lobby for value-maximizing TAC. In Chapter 3 of the thesis we apply a theoretical model to investigate challenges that confront fisheries’ management when implementing regulatory policies under IQ management system.

Studies, including Hilborn et al. (2005) and Arnason (1993) show that the ITQ system has registered successes in a number of Australian Fisheries; significant reduction in the fishing capital levels have generated substantial economic rents under ITQ. However, even in Australia, a number of fisheries managers continue to search for the most appropriate management system in order to ensure economic efficiency and sustainability. In Western Australia, for example, a recent assessment of the western rock lobster indicates that the state does not have preconceived idea as to
what the best management system is (Department of Fisheries, 2006). While theoretical examination and anecdotal evidence suggest these regimes are successful as management tools, empirical evidence on their effects is still limited (McWhinnie 2006). Individual rights systems, such as ITQ, aimed at fish stock recovery must be based on management systems that ensure correct identification of stock levels, set TACCs consistent with stock levels, as well as investments in the natural capital through the use of less destructive fishing methods. Effective fishery management methods must deal with the complex relationship between environmental and economic values, among others (Fletcher et al., 2005). It must also be recognized that each fishery in each region around the world has its unique characteristics such that the management system that works in one fishery is not necessarily advisable for another fishery. We note that while rights-based management regimes are increasingly recommended and implemented, they are not without problems (Arnason, 1999). This suggests that there is still the need for both theoretical and empirical work to be carried out, to establish which management strategies produce the optimal biological and economic outcomes. The three core chapters of this thesis (i.e., Chapters 3, 4 and 5) are a significant contribution in this direction.

Another issue of concern closely linked to the management challenge is over exploitation of the fish biomass. Over exploitation of fish stock around the world and management failure to reverse the negative impact of the practice is well documented in the literature. According to Conrad (2010) an estimated half of the world’s commercial fish stock is fully exploited and nearly a quarter is over exploited. For example, the presence of too many vessels in many fisheries is compelling evidence of widespread mismanagement leading to biological and economic over exploitation of the fish stock (Conrad, 2010). Various management options have been suggested in the literature as enforceable policies that might conserve fish stock and possibly serve as a hedge against resource uncertainty. Examples of
such policy measures include; establishment of marine reserve sanctuaries, individual private ownership systems, input and output restrictions.

Research has provided a number of options to help managers adopt options that may lead to optimal solutions that will ensure sustainability of the fish stock. For example, on the question of output seizure (a form of investment aimed at sustaining the stock, especially when the stock is considered to be in danger of depletion) Munro (1992) observes that if the stock of the fishery is below the resource target level, then the appropriate management policy would be that of forbidding harvesting entirely. This is because if the resource is over-exploited then the recovery could be economically painful as it will require sacrificing current consumption to re-grow the resource (Munro, 1992). This observation is supported by the Canadian Northern Cod TAC example where a drastic reduction in the TAC became necessary to avoid further depletion. In this particular case, Munro indicates that there was no dispute over the need for substantial resource investment, rather the argument was about the rate of investment. Another example is the closure of the orange roughy fishery to Australian vessels by Australian Fisheries Management Authority (AFMA) when the roughy population was threatened (Staples, 2003). Hartwick and Olewiler (1986) also emphasize that some restrictions (for example, gear restriction) may be imposed when a specific impact on the fish population is desired. For example, it may be advisable to ban all effort and harvests when biologists know that the fishery is reproducing. Their conclusion is that typically such restrictions have no effect on economic efficiency of the fishery.

Stock depletion, including species along the west coast of North America, was reversed through a combination of management strategies. These strategies involved legal size limit, seasonal closures, and adoption of the individual quotas (IQs) in British Columbia, California, and Alaska (Hilborn et al., 2005). Further examples
of success with the introduction of ITQs and other systems that provide incentives to individual operators that led to behaviours consistent with conservation, are provided by (Hilborn et al., 2005). The argument is that the system of governance established a framework where rewards for individual behaviour were consistent with socially desirable outcomes. They emphasize that there is no single prescription for success or failure. However, Long and McWhinnie (2012) show that a quota system may be simpler to implement to achieve social planner’s optimal solution. This strengthens the property rights theory of economic efficiency increasing monotonically in exclusivity.

Assessing Management Options

Varied models have been used to assess the success of different management options. The models used, however, have also raised questions. Conrad (2010), for instance, argues that earlier studies based on deterministic models are unlikely to reveal the value of a marine sanctuary in a stochastic marine environment. This view is shared by Grafton et al. (2006) who reveal that though deterministic bioeconomic models provide important insights about reserves, they understate the value of reserves to fisheries in a fluctuating environment. In line with these arguments Conrad proposes two models, deterministic and stochastic, to explain the possible effects of a marine sanctuary. Using these models Conrad finds results to suggest that though the deterministic model provides some useful optimal biomass level and harvest benchmarks that could be used for constructing total allowable catch (TAC) policy, a value of marine sanctuary is not likely to be revealed in a deterministic model in a stochastic marine environment. The stochastic model, on the other hand, shows that a marine sanctuary, through the migration process, reduces the variation in biomass compared to the ‘no sanctuary’ case where fishing was allowed based on TAC polices. As a result more detailed models of growth, migration, and
the effect of fishing practices, need to be constructed and analyzed before real-world fishing grounds are portioned into sanctuaries and smaller grounds (Conrad, 2010). Furthermore, the literature emphasizes the importance of economic considerations when establishing reserves and the need to explicitly model the endogeneity of fishing effort in a decision-making framework. The thesis acknowledges these concerns and incorporates into our models (particularly in Chapter 3) the stochastic nature of firms interaction with management and the consequent effect on the fish biomass in equilibrium. The question of violation, compliance, and punishment, investigated in Chapter 3 of the thesis is one way of explicitly modeling the endogeneity of fishing effort in the decision-making process in fisheries.

2.3 The Illegal, Unreported and Unregulated Challenge

An issue of great concern in the industry is the IUU challenge. IUU as the name stands is generally categorized under three main definitions. The illegal aspect of the practice refers to fishing activities conducted by national or foreign vessels under the jurisdiction of a state without permission, and or in contravention of the state’s laws and regulations. This means even vessels flying the flag of states party to relevant regional fisheries management organization but operating in contravention to the adopted regional conservation and management measures are considered illegal. It also implies that fishing activities that violate national laws or international obligations are considered illegal. Unreported activities, on the other hand, are those activities that are either misreported, or not reported at all to the relevant national authority. These are activities in contravention to national laws and

\[1\] These definitions are adapted from Agnew et al. (2009)
regulations. Unreported activities, in this regard, could also refer to activities undertaken in the area of competence of relevant regional fisheries body in violation of the organizations reporting procedures. Finally, a fishing activity is considered unregulated if it is conducted by vessels without nationality, or vessels flying the flag of a nation party to a relevant regional fisheries organization. Unregulated fishing also refers to activities by a fishing entity in a manner that is inconsistent with, and violates the conservation and management measures of the relevant regional organization. Fishing activities conducted in areas or for stocks in relation to which there are no applicable management measures, are considered unregulated. This means activities which are inconsistent with state responsibilities for the conservation of living marine resources under international law, are unregulated activities. These definitions show that IUU occurs in both national and international waters. Chapter 3 investigates the strategic interaction between fishers and management in the presence of IUU fishing, under individual fishing quota (IQ) and maximum economic yield scenarios. Various aspects of illegal activities and management regulatory challenges have been investigated in the past (see for example, Sutinen and Andersen, 1985a; Kuperan and Sutinen, 1998; Sutinen and Kuperan, 1999, and references there in).

The Effect of IUU on Fisheries

IUU practices sometimes reach extreme proportions and are of serious management, economic, and sustainability consequences (Clark, 1985; Ostrom, 1990; Charles et al., 1999). IUU contributes to over-exploitation of the fish stock, is a hindrance to the recovery of fish population and ecosystems, and negatively affects economic and social well-being of fishing communities. Global losses resulting from IUU are estimated to be between US$10 billion and US$24 billion annually (Agnew et al., 2009). This accounts for between 10% and 22% of total fisheries production value.
The problem is found to be worse in developing nations. In West African alone illegal catch is estimated at about 40% higher than reported catches (Agnew et al., 2009). The IUU practices not only affect sustainability, but are also of serious economic efficiency consequences. The IUU problem is widespread, nationally and internationally, and complex, yet finding solutions has eluded even the most advanced nations with sophisticated monitoring and surveillance devices.

An IUU challenge that cannot be ignored is the by-catch and discard problem which is also an aspect of the sustainability question. This challenge leads to uncertainty of the marine resource and poses serious sustainability challenge. The argument, as Munro(1992) rightly puts it, is that the challenges of resource uncertainty should be a major management concern and may require actions that can be difficult in terms of economic efficiency. In fact, an important consequence of resource uncertainty is the prescription of a more conservationist management policy (Munro, 1992). The implication, therefore, is that the issues of discard and by-catch should be incorporated into the management strategy to improve both the sustainability and the economic performance of the fishery. In the case of other IUU practices a number of measures have been suggested. These measures are to ensure compliance and meaningful reduction in IUU activities. The measures include: monitoring, control and surveillance activities. Enforcement through strong legal systems, involving effective methods of prosecution and realistic fines, is also suggested (Agnew et al., 2009). Chapter 3 of the thesis investigates management enforcement strategies in the quest to combat illegal fishing practices and preserve the fish stock. We do this by modeling the interaction between management and fishers as a two-person game to examine management strategies that give rise to compliance in the presence of IUU.

The above discussions establishes the link between fisheries as a natural capital, management options, and sustainability. However, the link is incomplete when the
rights question is left out of the discussion. We look at these issues in the Section that follows.

2.4 Property Rights and Sustainability

Sustainability concerns around the world continue to engage the attention of policy-makers, managers and fishers alike. This view is emphasised by Kompas et al. (2009). Unpredictable variabilities in resources and market forces introduce complexities and additional uncertainties into the fisheries industry, which if not properly managed can lead to sub-optimal economic outcomes (FAO, 2002). Sustainable economic efficiency in fisheries is specified under the assumption of optimum circumstances; i.e., market forces are expected to lead to economic efficiency (FAO, 2002). The idea that somehow some ‘invisible hand’ would regulate the market and ensure optimal market outcomes is found to rarely hold in fisheries because uncertainties and externalities often distort the natural selection of market forces in the industry. This, in fact, makes efforts to address the sustainability question a big challenge. For example, Hardin (1968) rejects the ‘invisible hand’ theory as a tool in the effective use of the commons (in this case marine resources); explaining that this does not ensure preservation and sustainability of natural resources, of which fisheries is an integral part.

The Importance of Property Rights in Fisheries

Property rights are integral components of the link identified above. The importance of property rights in capital accumulation is well recognized in economics. In fisheries property rights have been shown, theoretically and empirically, to create the incentive to promote the growth of the biomass and ensure sustainability. For
example, Squires et al. (2010) provide empirical evidence to support the theoretical prediction that the introduction of individual and transferable harvesting rights into a limited-entry and input-controlled fishery should result in an overall decline in excess capacity. Quotas for vessel owners meant less desperate racing and so less incentive to install every novelty in power or fishing gear (Scott, 1993).

In the context of specialization in production and trade, Arnason (1999) notes that property rights are more fundamental to economic progress than markets. The point is that rights safeguard individual interests and offer opportunities for mutual gains. This means the absence of property rights inevitably leads to low production level and less economic efficiency. Arnason (1999) hypothesizes that economic efficiency is monotonically increasing in three of four characteristics of property rights, namely; duration/permanence, security and exclusivity. Arnason, theoretically demonstrates that any small reduction in property rights security (increases in insecurity/uncertainty) results in monotonic reduction in economic efficiency, compared to what will be socially optimal. On the transferability/tradeability aspect of property rights, Arnason, demonstrates that efficiency is non-decreasing. The argument here is that with no transferability, there is no reason to believe that economic rents will continue to be generated. It is noted, however, that the cost of limited transferability can be high over time when the relative efficiency of any economic agent tends to decline.

We note from the above discussion that property rights in capital accumulation certainly have applications in the management of economic efficiency and sustainability in fisheries. Grafton et al. (2006), for instance, use the experiences of the British Columbia ground fish trawl fishery to demonstrate that the use of ITQs as a management approach promotes fisher behaviour that matches the goals required for economic efficiency and sustainable industry. Transferability of individual quota
allowed more profitable operators to increase their share of total catch, and also allow for greater specialization by fishers (Grafton et al., 2007). This contributes to a doubling in quota values. The views of Grafton et al., support the efficiency hypothesis of the property rights theory. Despite documented positive outcomes of rights-based management in the ‘capital accumulation’ equation in fisheries, sustainability and efficiency questions still remain. Chapter 3 of the thesis examines possible effects of property rights, in the form of ITQ, on profit efficiency in the South Australian Rock Lobster Fishery. Next, we discuss issues of economic efficiency in fisheries are discussed next.

2.5 Issues of Economic Efficiency: The Rights Argument

Preservation of the fish biomass is as important to the sustainability of the fishery industry as it is to economic efficiency in the industry. This means that, issues of sustainability cannot be isolated from any treatment of economic efficiency. A challenging issue in fisheries management, however, is finding a balance between economic efficiency and sustainability of the resource. Given that catch rate is important in the determination of economic efficiency in fisheries, any uncertainty in the biomass levels will have negative repercussions for industry economic efficiency. An example of such consequence is the closure of the orange roughy fishery to Australian vessels when the roughy population was threatened (Staples, 2003).

Private Property and economic Efficiency

Grafton et al. (2000) observe that despite the growing use of private property to help solve common-pool externalities there are few empirical studies that test for
changes in efficiency due to private property rights. Departing from previous trends
of the literature, Grafton et al. (2000) use data from natural experiments involving
common-pool resource to assess the changes in fishery following the introduction of
private harvesting in fishery. Previous literature used comparisons and qualitative
evidence. Grafton et al., also examine implications of attenuated rights on efficiency
and the efforts of different property right characteristics and producer surplus of
the firms. To test for changes in firms’ behaviour, efficiency and producer surplus,
the British Columbia Halibut Fishery is used as case study. Technical, cost, and
allocative efficiencies, as well as overall economic efficiency for each vessel relative to
a ‘best practice’ frontier isoquant calculated from a stochastic production frontier,
are estimated.

Results from the study suggest that ensuring an exclusive property right with good
quality of title is sufficient to yield substantial gains in revenues and producer
surplus. Further to that, it is suggested that gains in short-run cost efficiency
from privatization may not be instantaneous and may be limited by restrictions
on characteristics of the property right, especially transferability, divisibility, and
duration. To address the problem of cost in terms of long-run efficiency from the
bundling of property rights with capital, it is suggested that regulators need to
consider the impact of pre-existing regulations and institutional structures when
devising changes in property rights (Grafton et al., 2000).

Further argument in support of rights-based management, in the context of effi-
ciency, is provided by Dupont (2000). Providing evidence from British Columbia
Salmon Fishery, Dupont, argues that individual transferable vessel quotas (ITVQs)
may result in a number of efficiency gains. These gains may include the elimination
of capital-stuffing (i.e., the tendency to over invest in productive inputs; e.g., en-
gine, gear, hull, etc), transfer of harvesting rights to low cost vessels, encouragement
of profitable expansion of harvesting by individual vessels, and a more efficient mix
of vessels in the fleet. In addition, short-run gains associated with introduction of
ITQs result in the form of higher prices for quota species, supporting the belief that
ITQ programs encourage better quality catches and ultimately prices.

It is, however, argued that ITQ systems do not guarantee biological or economic
success, emphasizing that the poor performance of the British Columbia abalone
Fishery makes this clear (Hilborn et al., 2005). The observation is that there are
circumstances under which exclusive rights do not guarantee responsible fishing
practices. Such circumstances may arise because within fishing groups there is no
guarantee that the group will act in its self-interest, nor will the interest of the
individual within the group necessarily be the same as the group’s interest. This
means the dynamics and internal governance of the groups may not necessarily lead
to good economic outcomes. This emphasizes the earlier point raised, that finding
a balance between sustainability and economic efficiency is rather complex. As
earlier mentioned Chapters 4 and 5 of the thesis carries out empirical investigation
of efficiency issues, with Chapter 5 specifically examining the possible effect of
property rights (ITQ) on profit efficiency.

**Conclusion**

In this Chapter we have provided a broad overview of the fisheries literature con-
cerning sustainability, management, and efficiency. For example, the importance
of distinguishing between socio-economic processes that lead to increased efficiency
from investment in the fishery as capital, and the impact of such processes on sus-
tainability of exploitation, has been clearly stated. We have also highlighted some
of the most relevant parts of the literature that directly relate to the issues investigated in this thesis. Issues such as management challenges and failures, in the face of illegal activities, over-exploitation of the fish stock, as well as enforcement strategies as management options that may ensure sustainability and efficiency, have been discussed. In addition to this overall review, each subsequent chapter details the directly relevant literature.
Chapter 3

Inspection, Compliance and Violation: A Case of Fisheries

3.1 Introduction

The presence of destructive and illegal fishing activities is a major threat to sustainability of fisheries. Any type of fishing practice or activity that violates fisheries regulatory measures is considered illegal. Such activities may include unauthorized by-catch, discard, exceeding allowable quotas, the use of explosives, and the use of unauthorized fishing equipment such as unauthorized mesh-sizes, and others. Illegal activities are common and sometimes reach extreme proportions (Clark, 1985), and have been identified as a serious threat to the marine ecosystem.\footnote{The severity of the problem is well documented in the literature. See for example Pet-Soede and Erdmann, 1998; Halim and Mous, 2006; Costello and Guinness, 2010} The consequences of illegal, unregulated, and unreported (IUU) fishing activities have become a global concern in recent years.\footnote{For details on this, including the managerial and sustainability consequences, see Ostrom, 1990; Charles et al., 1999; Pitcher et al., 2002; Stokke, 2009, Pitcher et al., 2002, Pauly, 1989; FAO, 2002.} IUU fishing is found to contribute to the underestimation of stock levels and effort, undermine management programs, affect fish habitat, and is an inherently unsustainable fishing practice.
The need to control fishing effort and combat IUU activities requires the attention of fisheries managers around the world. In fact, Munro (1992) emphasizes that the problem of resource uncertainty requires that effort must be made to control fishing effort, and consequently harvest, in order to ensure some form of conservation and sustainability. According to Gordon (1954) one basic goal of fisheries management is to ensure that the benefits which the fisheries are capable of producing for society are neither wasted nor dissipated. The validity of Gordon’s point has been shown many times in the real world. Munro (1992) provides real world examples to show the validity of Gordon’s point. A basic challenge in fisheries, however, is finding a balance between economic efficiency, conservation and sustainability of the resource.

This Chapter examines the strategic interaction between fishers and management in the presence of IUU fishing with respect to output regulations. Specifically, the Chapter uses a game theoretic approach to consider the firm’s choice of legal and illegal effort to maximize profit in response to the fisheries manager’s choice of regulation, in the form of a harvest quota, and enforcement as: fines, inspection probabilities, and group classification. The interaction is modeled as a two-person dynamic game which gives rise to a steady-state equilibrium. This equilibrium characterizes the less-than-perfect enforcement strategy of the manager in response to firms’ compliance and violation behaviour. In addition, it allows consideration of the dynamic effect on fish stocks.

We show that fines, inspections and group classification, if properly applied, are important instruments that may help reduce the negative impact of illegal effort in fishing activities. The results also suggest that firms optimally choose the strategy of violate when in group 1 (where inspection probability is lower), and comply when assigned to group 2 (where inspection probability is higher). Firms’ illegal activities have been shown to place less value on the future of fisheries by using a
discount factor higher than that which will ensure sustainable harvest over time. The marginal product of the fishery is also eroded by the consequences of firms’ illegal behaviour when adopting illegal strategies to maximize economic profit. It must be noted that contrary to empirical evidence suggesting increasing maximum penalties considerably (Ostrom, 1990), the theoretical results in this Chapter indicate that punishment should have upper bound if it is to achieve the purpose for which it is intended. It is also argued that the compliance model developed in the Chapter, though based on individual fishing quota assumptions, is applicable and important under various systems of fisheries management as far as conservation and sustainability issues are concerned.

The application of game theoretic concepts to investigate various issues of fisheries is not uncommon in fisheries economics. For example, Long and Flaaten (2011) investigate potential cooperation in straddling stock fisheries when a coalition of countries act as a Stackelberg leader against the remaining singleton countries.\(^3\) What is uncommon, as far as we are aware, however, is the application of such concepts in the study of regulatory enforcement and compliance in fisheries economics. Andersen, Kuperan, and Sutinen have done some theoretical and empirical investigations on regulatory enforcement in the past (see for example, Sutinen and Kuperan, 1999; Kuperan and Sutinen, 1998; Sutinen and Andersen, 1985b). However, in theory the question of monitoring and enforcement in fisheries management studies remains largely ignored. Charles et al. (1999); Gibson et al. (2005); Coelho et al. (2008), provide evidence to suggest that theoretical investigation of monitoring and enforcement in fisheries management remains uncommon. Considering enforcement in the fisheries as a two-person game is consistent with theory, as done by Harrington (1988) in the emission regulation context, for example. Similar

\(^3\)For examples and details on these applications in fisheries see Munro, 1979, 1987; Sumaila, 1995; Jachmann and Billiouw, 1997; Trisak, 2005; Kronbak and Lindroos, 2007; Keane et al., 2008
applications can be found in Raymond (1999), Harford (1991, 2000), and Eckert (2004). These studies have considered the strategic role of environmental regulation and compliance, and have found that compliance is greater when violations are likely to be costly. Harrington applies game theory in environmental regulation as applied in the tax literature.

Enforcement can be difficult and costly, but if ignored the entire management system can be grossly endangered. Studies in illegal hunting, for instance, show that enforcement effort increases the incidence of poaching which negatively impacts wildlife population (Keane et al., 2008). Regulatory enforcement, through monitoring and punishment when violation is detected, is considered an integral part of successful conservation and natural resource management. The effect of enforcement designs on various management control systems in fisheries, forestry, wildlife poaching and, other conservation policies cannot succeed if managers are not able to influence behaviour of natural resource users (Jachmann and Billiouw, 1997; Ostrom, 1990; De Merode et al., 2007). Importantly, regulatory enforcement is found to be a necessary mechanism to solve a commons dilemma over time (Gibson et al., 2005).

The Chapter draws heavily on Harrington (1988) but also differs in a number of ways. Harrington (1988) investigates the dynamics of compliance and violation in relation to compliance cost. This Chapter, on the other hand, examines the effect of punishment on profits as the major determinant of compliance. Furthermore, whereas Harrington (1988) assumes the size of punishment in any period to be restricted, this Chapter assumes the size of punishment in any given period of the interaction is dependent on size of violation. These assumptions help to incorporate the underlying dynamics of fishery, particularly the dynamics of the fish stock.

Long and Flaaten (2011), and Clark (1985) analyze the efficiency, conservation and management challenges facing the resource.
To effectively analyse the effect of firms' effort choices on stock levels, it is important to understand why even firms that regularly comply may choose to violate at one time or the other. Moral and social considerations, besides economic gains, play a significant role in fisher decisions. The subgroup of profit maximizers, on whose behaviour social influence and moral obligation have little or no effect, may well account for the majority of violators (Kuperan and Sutinen, 1998). A firm may violate if it is losing money and there is potential to derive benefits from violation. This economic motive increases the probability of violation. The greed factor is also identified in the literature as a reason accounting for violation. The urge to increase profit even when already making profits can be a driving force for violation.\(^5\) Besides rent-seeking behaviour, over-capacity is also identified as a major economic cause of illegal fishing. In fact, subsidies that contribute to the maintenance, development, or transfer of fishing capacities are likely to artificially reduce the cost of IUU fishing capacities, both locally and internationally (Le Gallic and Cox, 2006). Cheap and ready labour in developing countries reduces operational costs and, in some circumstances, reduces the real cost of risk for vessel owners who are able to abandon and replace arrested crew members easily and at low cost (Agnew and Barnes, 2004).\(^6\)

The rest of the Chapter proceeds as follows. Section 3.2 describes the model, detailing the interaction between the manager and the firms, and the transition movements between groups. Section 3.3 discusses firms' effort choices when complying or violating in a single period under different management systems, and the consequences of this strategy given management enforcement instruments. Section 3.4 investigates a dynamic case of the violate and comply strategy. Section 3.5 concludes the Chapter, highlighting some policy implications of the strategic

\(^5\)For issues on how economic incentives override social and moral obligations and increase the incidence of violation, see for example; Charles et al. (1999) and Ostrom (1990).

\(^6\)Indonesia, China, and the Philippines, are cited examples of sources of IUU crews in recent times.
interaction between management and fishing firms.

3.2 The Model

The model considers interactions among the fisheries manager and $N \geq 2$ risk-neutral fishing firms. Throughout the Chapter, we use ‘fishing firms’, ‘firms’ and ‘fishers’ interchangeably to mean the same thing. The players interact a finite number of times. We use Harrington (1988)’s set-up to study monitoring and enforcement of renewable resource management using output restrictions. We investigate the relationship between a firm’s ‘compliance’ profit and the average level of compliance when both enforcement budget and the maximum penalty are limited, and further look at firms’ profits when complying and when violating.

It is assumed that any illegal fishing activity increases catch levels above some allowable quota, $\bar{h}$. For ease of analysis a non-transferable individual quota (IQ) regime is assumed. In reality quota can be transferable/tradeable or non-transferable as explained in Chapter 2. We consider $N$ firms with fixed capital, who have identical marginal cost, $c$, in competitive market setting. The assumption of competitive market environment is in reference to output sales and not in terms of quota transfers. Firms take the biomass, $B$, in each period as given.

This Section investigates a steady-state equilibrium in a dynamic game with two groups, two players and two possible actions. Subsection 3.2.1 explains the manager’s problem, Subsection 3.2.2 explains the firm’s problem in any given period. Here profit maximizing behaviour of firms within an output controlled regulatory environment with imperfect inspection is explained. Subsection 3.2.3, before characterizing the dynamic model, explains the transition movements. The fisheries managers enforcement strategy is then investigated in Subsection 3.2.4.
3.2.1 The fisheries manager

At the start of any period the manager sets an individual fishing quota, \( \bar{h} \), the maximum allowable harvest level for that period. Fishers may choose to conduct illegal activities of catching an additional \( h' \) above the legal amount, giving a total harvest of \( h = \bar{h} + h' \). At the beginning of the game, the manager separates all the fishers into two groups, \( G_1 \) and \( G_2 \). In every period, the manager has the following actions: inspect, or not inspect. It is assumed the manager chooses the probabilities \( \mu_i \) of inspecting firms in Group \( i \). The inspection probabilities are chosen so that the conditions \( \mu_2 > \mu_1 \) and \( \mu_2 + \mu_1 = 1 \), always hold. This means the manager would inspect a firm in group 2 more often than he/she would inspect a firm in group 1. The differential inspection probability here is based on the assumption that the manager knows from experience that firms in group 2 are likely to violate more often. In addition, it is also assumed that the probability of inspection is not affected by the incidence of a violation. The definition of inspection probabilities in this Chapter differs from Harrington (1988), where \( \mu_1 \), and \( \mu_2 \), are chosen randomly and the conditions above not imposed. If the manager inspects a firm and discovers a violation, then that firm pays a penalty/fine and is moved to \( G_2 \) if in \( G_1 \), or remains in \( G_2 \) with certainty if already in \( G_2 \). If the manager inspects a firm and finds that it is complying, the firm is moved to \( G_1 \) with probability \( \eta \), if in \( G_2 \), as a form of reward, or remains in \( G_1 \) with certainty if already in \( G_1 \). Notice that the transfer from group 2 to group 1 is random. This is explained by the fact that the transfer is a reward given at the manager’s discretion and not to be assumed, by firms, with certainty. It is also to ensure good behaviour at all times.

Previous work including Charles et al. (1999), De Merode et al. (2007) and Becker (1968) make the assumption that a fisher faces some probability, \( \theta \), of being detected and punished. This Chapter does not make this assumption. Instead, it is assumed
here that once a firm is inspected a violation is detected without error. It is also assumed that a violating firm pays the fine,

\[ F = f h' \]

if convicted. The scale of fine, \( f > 1 \), is chosen by the manager to give firms with highest compliance cost incentive to comply. The fine increases with \( h' \), the level of illegal activity. \( F = f h' \), means that under risk-neutrality assumption not every firm is inspected, but once inspected violation is detected and punished. In this formulation it is assumed the occurrence of a violation can either be detected or suspected off site, thus raising the probability of an inspection. Here the firm is certain about the value of punishment it faces once caught, and factors that into its profit-maximizing behaviour when violating. This also means that the size of violation is dictated by the effect of punishment on expected profit since size of punishment is known in advance. This is as opposed to \( F = \theta h' \), which is based on the assumption that everyone is inspected but violation is detected with some probability, \( \theta \). In this formulation there is no certainty about size of punishment if managers do not announce in advance what the inspection probability would be. Furthermore, since this formulation is also based on the assumption that punishment is restricted, firms may not care about how much they violate given that cost is the only concern. This does not fit well in the fishery’s case where stock dynamics are a major concern of managers. In Harrington (1988) \( F \) is not given explicit definition.

The general economics of crime and punishment shows that risk-neutral individuals will only engage in a criminal activity if and only if their private expected gains exceed the expected sanctions for doing so (Becker, 1968; Stiegler, 1971). The specific structure of penalties, since Becker (1968), has thus been considered important

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The manager’s overall objective is to maximize the sustainable value of the fishery. Within this, with respect to enforcement, the manager’s objective is to minimize frequency of violation, subject to fixed enforcement budget. The probabilities of inspection, $\mu_i$, and reward, $\eta$, are chosen to minimize the average inspection rate in steady-state to reduce inspection cost. The manager maximizes the target compliance rate in steady-state, and chooses the scale of the punishment/fine, $f$. We note that Charles et al. (1999), for example, investigate avoidance activities given input or output controls, and enforcement levels necessary to achieve specified conservation goals. This differs from this chapter in the sense that it does not investigate compliance levels and so does not use a reward system to ensure compliance. Assuming risk-neutrality Sutinen and Andersen (1985b) examine cost of regulatory enforcement and argue that costly imperfect enforcement negatively impact optimal stock level. While they assume imperfect enforcement, i.e., not every violator is detected and punished, we assume that once inspected violation is detected and punished. Again, in their formulation cost of enforcement is the main instrument. We use punishment and reward as incentives to induce compliance. Based on earlier empirical investigation (Kuperan and Sutinen, 1998), Sutinen and Kuperan (1999) assume risk-aversion and investigate the effect of moral and social obligations on

---

7 See also Green and McKinlay (2009).
compliance. They find that increases in penalty and probability of detection only reduces the number of violators with no deterrence effect on the remaining violators, and that social and moral obligations further explain individual compliance behaviour. We note that by incorporating incentive mechanism, in the form of reward, in our set we are able to capture some component of compliance behaviour that is not fully explained by punishment alone as pointed out by Sutinen and Kuperan (1999). Further to that we also note, as our results will show, that the outcome, when risk-aversion, is assumed is no different from what we observe when risk-neutrality is assumed. This confirms Becker’s assertion earlier mentioned.

3.2.2 The firms

A firm chooses whether to comply \((c)\) or violate \((v)\) with a set of regulations. It is assumed that the firms’ violating behaviour is to increase harvest by \(h'\) above the allowable quota, \(\bar{h}\), in a given fishing period. Firms complying earn ‘compliance’ profit, \(\pi_c\), while those violating earn ‘violation’ profit, \(\pi_v\). Firms internalize penalties for violating regulations like any operational cost. Were the manager to announce in advance what the inspection probability would be, a firm’s optimal behaviour is non-random. The firm in that case is better off complying with certainty (that is, with probability 1) if \(\pi_c > \pi_v - \mu_i\bar{F}\), and violating otherwise, assuming that \(\mu_i\) and \(\bar{F}\) are large enough. Firms take other firms’ actions, as well as the stock level, \(B\), as given. Price, \(p\), and harvesting cost are also taken as given under competitive market conditions. The analysis uses a harvesting function: \(h = qeB\), where \(q\) is catchability coefficient, \(e\) is the fishing effort, and \(B\) is the fish biomass. In a given period all firms complying earn the same profit. This profit is referred to as ‘compliance’ profit, \(\pi_c\), and is given by:
\[ \pi_c = (pqB - c)e \] (3.1)

The cost of harvesting is simply \( ce \), where \( c \) is the constant managerial cost of effort. It is important to note that compliance profit is the same whether the firm is group 1 or group 2, that is, \( \pi_{1c} = \pi_{2c} \equiv \pi_c \).

Let the allowable quota, \( \bar{h} \), be defined as: \( \bar{h} = qe^L B \), where \( e^L \) and \( B \), are legal effort and the fish stock, respectively. Defining harvest above \( \bar{h} \) as \( h' = h - \bar{h} \), let \( h = e^{IL} qB + qe^L B \), and \( h' = e^{IL} qB \), where \( e^{IL} \) is illegal effort. The assumption is that when firms violate they choose some amount of illegal effort in addition to legal effort. Hence total effort when violating is defined as: \( e^T = e^{IL} + e^L \). This means that under compliance firms’ total effort will be equal to legal effort; that is, \( e^T = e^L \equiv e \). For group 1 firms violating, the ‘violation’ profit, exclusive of expected fine, will be:

\[ \pi_{1v} = (pqB - c)e^L + (pqB - c)e^{IL} \] (3.2)

and they will pay a fine, if inspected, with expected value of \( \mu_1 qBe^{IL} \). In reality not all violators are punished, especially first time violators (Green and McKinlay, 2009). Similarly, the profit for group 2 firms violating, exclusive of expected fine, can be expressed as:

\[ \pi_{2v} = (pqB - c)e^L + (pqB - c)e^{IL} \] (3.3)

but the expected value of the fine will be \( \mu_2 qBe^{IL} \), which is higher than the value of group 1 firms’ expected fine. In line with Harrington (1988) it must be observed
here that in static analysis the fisheries manager and firms do not have a way of reacting to each other’s actions since the game is one shot game. Given expected penalty as a function of rate of violation the firms make a single choice of violate or comply.

### 3.2.3 Description of transition movements (two state model)

In this set up, a two-state model in which firms are moved between groups based on their compliance history is assumed. A firm found complying in $G_2$ upon inspection is returned to $G_1$ with probability, $\eta$. Thus the firms and the manager are players in a pair of linked games with payoff matrices shown in Table 3.1 below.

<table>
<thead>
<tr>
<th></th>
<th>\text{\textit{Group 1}} ($G_1$)</th>
<th>\text{\textit{Group 2}} ($G_2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>\text{Comply}</td>
<td>$\pi_{1c}$</td>
<td>$\pi_{2c}$</td>
</tr>
<tr>
<td>\text{Violate}</td>
<td>$\pi_{1v}$</td>
<td>$\pi_{2v}$</td>
</tr>
<tr>
<td>\text{\textit{No inspection}} $(1 - \mu_1, 1 - \mu_2)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>\text{\textit{Inspection}} $(\mu_1, \mu_2)$</td>
<td>$\pi_{1c}$</td>
<td>$\pi_{1v} - F$</td>
</tr>
</tbody>
</table>

A firm violating in $G_1$ achieves profit $\pi_{1v}$ if there is no inspection. Notice that $\pi_{1v} > \pi_{1c}$ because a violating firm’s harvest is greater than that of a complying firm, that is, $h > \bar{h}$. However, if there is inspection a firm violating in $G_1$ receives $\pi_{1v}$ but is also punished with a fine, $F$, and moved to $G_2$ with certainty. If there is inspection a firm complying in $G_2$ earns compliance profit and a chance, $p(\rightarrow G_1) = \eta$, of being moved to $G_1$. This inspection and enforcement process poses
a Markov decision problem for the firm (Kohlas and Schmidt, 1982; Harrington, 1988). Strategies are independent of history and are only conditional on which group the firm is in. More generally a firm’s movement from group to group is according to transition probabilities that depend on the current group and the firm’s action taken in that period; that is, comply or violate. Further, a firm’s payoff in each period is dependent on the group and the action taken. In the following matrix firms’ transition probabilities, $\mu_i^{[a]}$, are described. The superscript $[a = 0, 1]$ indicates a firm’s action comply, or violate, respectively, and $i = 1, 2$, as earlier defined.

<table>
<thead>
<tr>
<th></th>
<th>Comply ($a = 0$)</th>
<th>Violate ($a = 1$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$G_1$ $G_2$</td>
<td>$G_1$ $G_2$</td>
</tr>
<tr>
<td>$G_1$</td>
<td>1 0</td>
<td>1 $-\mu_1$ $\mu_1$</td>
</tr>
<tr>
<td>$G_2$</td>
<td>$\mu_2\eta$ $1-\mu_2\eta$</td>
<td>0 1</td>
</tr>
<tr>
<td>Panel (a)</td>
<td></td>
<td>Panel (b)</td>
</tr>
</tbody>
</table>

From panel (a) of Table 3.2, observe that a $G_1$ firm complying remains in $G_1$ with certainty, that is, probability 1. In other words, the probability of moving a $G_1$ firm which is complying, to $G_2$, is 0. Panel (b), on the other hand, shows that the probability of a $G_1$ firm violating, and remaining in $G_1$ or being moved to $G_2$ is $1-\mu_1$ or $\mu_1$, respectively. The probabilities of a $G_2$ firm’s movements between groups is explained analogously.

Let $S_{ij}$ be the strategy space from which a firm in $G_i$ adopts a specific strategy $s_{ij} \in S_{ij}$ to optimize its payoff following a specific action by the fisheries manager. Here the subscripts, $ij$, take on discrete values 0 or 1 and denote the actions: comply
or violate, in different groups. The manager’s action is a specific regulation or set of regulations. In this setting a *decision* at any period is a mapping from groups to actions, and a strategy [policy] is a sequence of decisions over time. A strategy $s_{ij}$ for the firm is a mapping $s_{ij} : \{G_1, G_2\} \rightarrow \{0, 1\}$; i.e., a mapping of groups into decisions either to comply or violate a regulation or set of regulations. Notice that in any two given periods of the game, firms in either group can decide to do the following: comply ($C$) in both groups; comply, when in group 1 and violate ($V$), in group 2; violate in group 1 and comply in group 2; or violate in both groups. For the firms in the two groups, Table 3.3 summarizes the compliance strategy described here. The actions: $C, C$ – comply in both groups; $C, V$ – comply in group 1 and violate in group 2; $V, C$ – violate in group 1 and comply in group 2; and $V, V$ – violate in both groups. This Chapter makes the following observation. As Harrington (1988) rightly points out, the degree of noncompliance is important in real world situations where the occurrence of certain violations is continuous; for example, in the case of environmental pollution. However, in this model a firm makes discrete choices; comply, or violate.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>$G_1$</th>
<th>$G_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s_{00}$</td>
<td>$C$</td>
<td>$C$</td>
</tr>
<tr>
<td>$s_{01}$</td>
<td>$C$</td>
<td>$V$</td>
</tr>
<tr>
<td>$s_{10}$</td>
<td>$V$</td>
<td>$C$</td>
</tr>
<tr>
<td>$s_{11}$</td>
<td>$V$</td>
<td>$V$</td>
</tr>
</tbody>
</table>

Table 3.3: Firms Strategy matrix

Next we consider firms’ expected profits and analyse their strategic behaviour in a dynamic setting.
3.2.3.1 Firms’ expected profit functions in the dynamic model

Before analyzing firms’ strategic behaviour in detail, firms’ expected profits following their response to the manager’s inspection and penalties is explained. Let \( E^{ij}[\pi_{Gi}] \) be the the discounted present value of expected profit of a firm, \( i \), when in \( G_i \) adopting a strategy \( s_{ij} \). Profits are discounted with discount factor, \( \beta \); where, \( 0 \leq \beta < 1 \). Assuming that firms’ profits follow a stationary process over time, the expected present value of a firm in \( G_1 \) adopting strategy \( s_{00} \), is the profit when complying this period, plus the discounted expected present value in the next period. This is expressed as;

\[
E^{11}[\pi_{1v}] = \pi_{1v} - \mu_1 F + \mu_1 \beta E^{11}[\pi_{2c}] + (1 - \mu_1) \beta E^{11}[\pi_{2c}] \tag{3.4}
\]

\[
E^{00}[\pi_{1c}] = \pi_{1c} + \beta E^{00}[\pi_{1c}] \tag{3.5}
\]

Similarly, by the stationary property, the expected present value of a firm in \( G_2 \) adopting strategy \( s_{00} \), is expressed as;

\[
E^{00}[\pi_{2c}] = \pi_{2c} + \mu_2 \eta \beta E^{00}[\pi_{1c}] + (1 - \mu_2 \eta) \beta E^{00}[\pi_{2c}] \tag{3.6}
\]

This means that the expected profit, in present value, of a \( G_2 \) firm adopting strategy \( s_{00} \), is the profit when complying in the current period, plus the expected profit discounted one period when; either transferred to \( G_1 \) and complying or remaining in \( G_2 \) and complying. For strategy \( s_{11} \), using the stationary property assumption, the expected profit, in present value, of a \( G_1 \) firm violating in both groups is expressed as:
\[ E^{11}[\pi_{1v}] = \pi_{1v} - \mu_{1}F + \mu_{1} \beta E^{11}[\pi_{2v}] + (1 - \mu_{1}) \beta E^{11}[\pi_{2v}] \] 

(3.7)

This is to say that the expected profit, in present value, of a \(G_{1}\) firm adopting strategy \(s_{11}\) is the profit when violating in current period minus the punishment, plus the expected profit discounted one period when: either transferred to \(G_{2}\) and violating or remaining in \(G_{1}\) and violating. The expected profit, in present value, of a \(G_{2}\) firm adopting strategy \(s_{11}\), by the stationary property, is analogously expressed as:

\[ E^{11}[\pi_{2v}] = \pi_{2v} - \mu_{2}F + \beta E^{11}[\pi_{2v}] \] 

(3.8)

The four sets of simultaneous equations giving the present values of strategies \(s_{00}\), \(s_{01}\), \(s_{10}\) and \(s_{11}\) are stated in the matrix in Table 3.4.

Table 3.4: Matrix of firms’ expected profits when complying or violating

<table>
<thead>
<tr>
<th></th>
<th>Comply (0)</th>
<th>Violate (1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(G_{1})</td>
<td>(E[\pi_{1c}] = \pi_{1c} + \beta E[\pi_{1c}])</td>
<td>(E[\pi_{1v}] = \pi_{1v} - \mu_{1}F + \mu_{1} \beta E[\pi_{2v}] + (1 - \mu_{1}) \beta E[\pi_{1v}])</td>
</tr>
<tr>
<td>(G_{2})</td>
<td>(E[\pi_{2c}] = \pi_{2c} + \mu_{2} \beta E[\pi_{1c}] + (1 - \mu_{2}) \beta E[\pi_{2c}])</td>
<td>(E[\pi_{2v}] = \pi_{2v} - \mu_{2}F + \beta E[\pi_{2v}])</td>
</tr>
</tbody>
</table>

Solving these simultaneous equations gives the present values of the strategies.\(^8\) Unless essentially required for explanation, superscripts may sometimes be dropped for convenience. It was earlier established that \(\pi_{1c} = \pi_{2c} \equiv \pi_{c}\), thus \(\pi_{1c}\), and \(\pi_{2c}\), are replaced with \(\pi_{c}\).

\(^8\)Appendix A.1 explains how Equations 3.5 to 3.8 are derived.
3.2.3.2 Solution summary

The following Table (Table 3.5) summarizes results obtained from solving the above system of equations.\footnote{See Appendix B for derivations.}

Table 3.5: Firm expected profits for different strategies

<table>
<thead>
<tr>
<th>Strategy</th>
<th>$E^{ij}[\pi_{c_1}]$</th>
<th>$E^{ij}[\pi_{c_2}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s_{00}$</td>
<td>$\frac{\pi_c}{1 - \beta}$</td>
<td>$\frac{\pi_c}{1 - \beta}$</td>
</tr>
<tr>
<td>$s_{01}$</td>
<td>$\frac{\pi_c}{1 - \beta}$</td>
<td>$\frac{\pi_{2v} - \mu_2 F}{1 - \beta}$</td>
</tr>
<tr>
<td>$s_{10}$</td>
<td>$\frac{\beta \mu_1 \pi_c + (\pi_{1v} - \mu_1 F)(1 - \beta(1 - \mu_2 \eta))}{(1 - \beta)[1 - \beta(1 - \mu_1 - \mu_2 \eta)]}$</td>
<td>$\frac{\pi_c[1 - \beta(1 - \mu_1)] + \beta \mu_2 \eta(\pi_{1v} - \mu_1 F)}{(1 - \beta)[1 - \beta(1 - \mu_1 - \mu_2 \eta)]}$</td>
</tr>
<tr>
<td>$s_{11}$</td>
<td>$\frac{(1 - \beta)(\pi_{1v} - \mu_1 F) + \mu_1 \beta(\pi_{2v} - \mu_2 F)}{(1 - \beta)[1 - \beta(1 - \mu_1)]}$</td>
<td>$\frac{\pi_{2v} - \mu_2 F}{1 - \beta}$</td>
</tr>
</tbody>
</table>

Lemma 1. Strategy $s_{01}$ is not optimal

The proof is in Appendix A.2 [C]. When $\pi_c > \pi_{2v} - \mu_2 F$, a firm’s best response is to comply in both groups since it is more costly to violate in $G_2$, which means $s_{00}$ is preferred to $s_{01}$. When $\pi_c < \pi_{2v} - \mu_2 F$, a firm is better off violating in both groups $G_1$ and $G_2$, which means $s_{11}$ is preferred to $s_{01}$. This means strategy $s_{01}$ is never optimal.

The underlying assumption of lemma 1, is that firms are rational and violation is motivated by rent-seeking behaviour. This means if punishment makes violation
costly and compliance is more profitable then a firm’s preference would be to comply in both groups 1 and 2, satisfying the first statement of lemma 1. On the other hand, under the given assumption, a firm violates if and only if gains from violation, given punishment, exceed gains from compliance. In that case a firm’s preference is to violate in both groups $G_1$ and $G_2$, satisfying the second statement of lemma 1.

Next, consider the expected profits of a firm in group $i$, $E^{ij}[\pi_{Gi}]$, of the remaining strategies as functions of compliance profit, $\pi_c$, in the form $A + B\pi_c$:

Let the expected profit of a firm in group 1 which always complies be expressed as; $E^{00}[\pi_{G_1}]$: $A = 0$, and $B\pi_c = \frac{\pi_c}{1 - \beta}$, that is, $B = \frac{1}{1 - \beta}$, and $\beta \neq 1$ implying $B > 0$; similarly the expected profit of a firm which violates when in group 1 and complies when in group 2 is expressed as; $E^{10}[\pi_{G_1}]$: $A + B\pi_c$; implying $A > 0$, $B > 0$; and the expected profit of a firm which violates when in group 1 and violates when moved to group 2 is expressed as; $E^{11}[\pi_{G_1}]$: $A + B\pi_c$; implying $A > 0$, $B = 0$.

**Lemma 2.** Firms are indifferent between strategies $s_{00}$ and $s_{10}$.

The proof is in Appendix A.2 [C]. Setting either $E^{00}[\pi_{G_1}]$ to $E^{10}[\pi_{G_1}]$, or $E^{00}[\pi_{G_2}]$ to $E^{10}[\pi_{G_2}]$ and solving for $\pi_c$ an expression for $L_0$, the leverage or expected profit from violation, is obtained. For $L_0 \equiv \pi_c$, that is complying when $\pi_c = \pi_{1v} - \mu_1 I \equiv L_0$, it can be established that $E^{00}[\pi] = E^{10}[\pi] > E^{11}[\pi]$. This means that payoffs to strategies $s_{00}$ and $s_{10}$ become identical and firms are indifferent between the two.

Based on the assumption under lemma 1, a firm violates in any future period if expected profit from violation exceeds expected profit from compliance in any given
group. This implies that when expected profits from any two strategies are identical a firm is indifferent between such strategies. In this case when expected profit from the strategy of complying in \(G_1\) and \(G_2\) is identical to the expected profit from the strategy of violating in \(G_1\) and complying in \(G_2\), the firm would be indifferent between the two strategies. This satisfies lemma 2.

Let us now investigate what happens in other strategy cases by solving for compliance profit, \(\pi_c\), and analyzing the leverage, \(L\), as before. Solving for \(\pi_c\) by either equating \(E^{10}[\pi_{G_1}]\) to \(E^{11}[\pi_{G_1}]\), or \(E^{10}[\pi_{G_2}]\) to \(E^{11}[\pi_{G_2}]\), and expressing the result as \(L_1\) the following is obtained:

\[
L_1 \equiv \pi_c = (\pi_{2v} - \mu_2F) - \frac{\beta \mu_2 \eta[(\pi_{1v} - \mu_1F) + (\pi_{2v} - \mu_2F)]}{1 - \beta(1 - \mu_1)}.\quad (3.9)
\]

It can be verified that when \(L_1 \equiv \pi_c < \pi_{2v} - \mu_2F\), \(E^{10}[\pi] = E^{11}[\pi] > E^{00}[\pi].\) This means that when expected profit from violation in \(G_2\) is greater than expected profit from compliance, then expected profit from the strategy of violating in \(G_1\) and complying in \(G_2\), is equal to the expected profit of the strategy of violating in both \(G_1\) and \(G_2\), and greater than the expected profit from the strategy of complying in \(G_1\) and \(G_2\).

Summary of a firm’s optimal strategy choices, \(\phi\), can be given as:

\[
\phi = \begin{cases} 
  s_{00} & \text{if} & \pi_{1v} - \mu_1F \leq L_0 \\
  s_{10} & \text{if} & L_0 \leq \pi_{1v} - \mu_1F \leq L_1, \\
  s_{11} & \text{if} & L_1 \leq \pi_{1v} - \mu_1F
\end{cases}
\]

\(^{10}\)See derivations in Appendix A.3.
Given that $\mu_2 F > \mu_1 F$, $L_1$ must be at least less than $\pi_{2v} - \mu_2 F$, the expected payoff when a firm violating in $G_2$ is punished. In degenerate cases the following will occur:

(a) $L_1$ will equal $\pi_{2v}$, when there is no inspection in $G_2$, that is, when $\mu_2 = 0$;

(b) $L_1$ will equal $\pi_{2v} - \mu_2 F$, when $\beta = 0$ (perfect myopia);

(c) $L_1$ will equal $\pi_{2v} - \mu_2 F$, when $\eta = 0$, that is, when firms complying in $G_2$ are not rewarded with transfers to $G_1$;

(d) $L_1$ will equal $\pi_{2v} - \mu_2 F$, when $\pi_{2v} - \pi_{1v} = 0$, and $\mu_1 F - \mu_2 F = 0$.\(^\text{11}\)

In all other cases $L_1 < \pi_{2v} - \mu_2 F$, must hold. Thus firms are classified as $s_00$, $s_{10}$, or $s_{11}$ firms, based on their optimum strategies which also depend on their ‘compliance’ profits and the enforcement parameters chosen by the manager. Given the probability that an $s_{ij}$ firm is in compliance is $\lambda_{ij}$, a firm complies with probability $\lambda_{00} = 1$, and violates with probability $\lambda_{11} = 0$. A firm choosing strategy $s_{10}$ violates in $G_1$ and complies in $G_2$. This strategy presents an interesting case because a firm is in compliance only part of the time. When this strategy, $s_{10}$, is optimum the transition matrix in Table 3.6 can be observed.

\[
\begin{array}{ccc}
\hline
\text{Group} & G_1 & G_2 \\
\hline
G_1 & 1 - \mu_1 & \mu_1 \\
G_2 & \mu_2 \eta & 1 - \mu_2 \eta \\
\hline
\end{array}
\]

\(^{11}\text{From Equations (3.2 and 3.3) it can be verified that when } \pi_{2v} - \pi_{1v} = 0, \mu_1 F - \mu_2 F = 0.\)

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With this strategy a firm violates when in $G_1$, but complies in $G_2$. The frequency of compliance in steady-state is the stationary probability of being in $G_2$, given as:

$$\lambda_{10} = \frac{\mu_1}{\mu_1 + \mu_2 \eta}.$$

In steady-state the manager inspects firms adopting strategy $s_{ij}$ with probability $\psi_{ij}$. This means in steady-state firms complying in both groups $G_1$ and $G_2$ are inspected with probability $\psi_{00} = \mu_1$, and those violating in both groups are inspected with probability $\psi_{11} = \mu_2$. In steady-state $s_{00}$ firms are in $G_1$ with certainty. Strategies $s_{00}$ and $s_{11}$ are absorbing states; firms in these states remain there forever. Likewise, firms with strategy $s_{11}$, in steady-state, are in $G_2$ with certainty. It follows that in steady-state the manager inspects firms with $s_{10}$ strategy in either state with probability,

$$\psi_{10} = \frac{\mu_2 \eta}{\mu_1 + \mu_2 \eta} \frac{\mu_1}{\mu_1 + \mu_2 \eta} + \frac{\mu_1}{\mu_1 + \mu_2 \eta} \frac{\mu_2}{\mu_1 + \mu_2 \eta} = \frac{\mu_1 \mu_2 (1 + \eta)}{\mu_1 + \mu_2 \eta}.$$ (3.10)

Equation (3.10) can be explained as the probability that a firm is in group 1, multiplied by the probability of inspection in group 1, plus the probability of the firm being in group 2, multiplied by the probability of inspection in group 2. Notice that for $\lambda_{00} = 1$, and $\lambda_{11} = 0$, it can be observed that $\lambda_{00} > \lambda_{10} > \lambda_{11}$. Also, when $\psi_{00} = \mu_1$, $\psi_{11} = \mu_2$, and $\mu_1 < \mu_2$, it implies that $\psi_{00} < \psi_{10} < \psi_{11}$. This means firms with good compliance history are inspected less.

### 3.2.4 Fisheries manager’s enforcement strategy

This Section analyses the fisheries manager’s enforcement strategy. Since enforcement is costly, the manager’s goal is to minimize resources employed in monitoring
and enforcement, while achieving a target compliance rate. To do this, the manager may want to modify the following four parameters: the inspection frequencies $\mu_1$ and $\mu_2$, the probability of transfer $\eta$, and the fine, $F$.

The following describes the leverage in this case. Suppose that for any given violation there is a maximum allowable penalty, $F_{\text{max}}$. Let $\Omega$ be the steady-state target compliance rate. Let $\Pi_c$ be the set of all compliance profits such that $\pi_c \in \Pi_c$, and any firm with profit $\pi_{c_{\text{max}}} \in \Pi_c$, where $\pi_{c_{\text{max}}} = \text{supremum (lower upper bound) of } \Pi_c$, complies with probability $\Omega$. Let us also define $\Pi_v$ as the set of all violation profits for firms violating, such that $\pi_v \in \Pi_v$, with $\pi_{v_{\text{max}}} = \text{supremum of } \Pi_v$, and $\Delta = \pi_{v_{\text{max}}} - F_{\text{max}}$, where $\Delta$ is the leverage of the enforcement strategy for the compliance rate, $\Omega$. Then for perfect compliance, that is, for $\Omega = 1$, $F_{\text{max}} > \pi_{v_{\text{max}}}$. This is to say that in equilibrium the manager aims at perfect compliance and so modifies the inspection frequencies, $\mu_1$ and $\mu_2$, together with the probability of transfer $\eta$, in order to ensure that equilibrium maximum punishment exceeds equilibrium maximum violation profit. On the other hand, there is no compliance if $\pi_{v_{\text{max}}} - F_{\text{max}}/(1 - \beta) > \pi_{c_{\text{max}}}$; that is, if maximum ‘violation’ profit, less discounted maximum future penalties, exceed maximum compliance profit.

In Section 4 of this paper, it is argued that some firms, for various reasons, are not deterred by punishment/penalties and therefore violate even when making losses. It can, however, be shown that some amount of compliance is achievable even if maximum violation profit, after accounting for discounted maximum future penalties, is negative, that is, $\pi_{v_{\text{max}}} - F_{\text{max}}/(1 - \beta) < 0$. From $L_1 \equiv (\pi_{2v} - \mu_2F) + \frac{\beta\mu_2\eta[\pi_{2v} - \pi_{1v} + \mu_1F - \mu_2F]}{1 - \beta(1 - \mu_1)}$, the leverage discussed earlier, it can be noted that if $F = F_{\text{max}}$, $\mu_2 \approx \eta = 1$, and $\mu_1 = \varepsilon$, where $\varepsilon$ is sufficiently small
value such that $\varepsilon \in ]0, 1[$, then

$$L_1 \equiv \pi_2 v - \psi_{\text{max}} + \frac{\beta (\pi_2 v - \pi_1 v + \varepsilon \psi_{\text{max}} - \psi_{\text{max}})}{1 - \beta (1 - \varepsilon)} = \frac{\pi_2 v (1 + \varepsilon \beta) - \beta \pi_1 v}{1 - \beta (1 - \varepsilon)} - \frac{\psi_{\text{max}}}{1 - \beta (1 - \varepsilon)}$$

(3.11)

If maximum violation profits in both $G_2$ and $G_1$ are equal, that is, if $\pi_2 = \pi_1 \equiv \pi_{\text{v}}^{\text{max}}$, then $L_1 \equiv \pi_{\text{v}}^{\text{max}} - \frac{\psi_{\text{max}}}{1 - \beta (1 - \varepsilon)}$. Given that $\varepsilon$ is sufficiently small, this result implies that $L_1$ can be as close as possible to $\pi_{\text{v}}^{\text{max}} - F_{\text{max}} / (1 - \beta)$, that is, $L_1 \approx \pi_{\text{v}}^{\text{max}} - F_{\text{max}} / (1 - \beta)$. If the manager’s target compliance rate, $\Omega$, in steady-state is such that $\Omega < 1$ and for some $\pi_{\text{v}}^{\text{max}} < F_{\text{max}} / (1 - \beta)$, some amount of compliance is feasible, then the manager’s optimization problem is to minimize $\psi_{10}$ with respect to $\mu_1, \mu_2, F$, and $\eta$,\footnote{See Appendix A.3 for derivations}

that is,

$$\text{Min } \psi_{10} = \frac{\mu_1 \mu_2 (1 + \eta)}{\mu_1 + \mu_2 \eta}$$

(3.12)

s.t.

$$L_1 = \pi_2 v - \mu_2 F + \frac{\beta \mu_2 \eta \pi_2 v - \pi_1 v + \mu_1 F - \mu_2 F}{1 - \beta (1 - \mu_1)} \leq \pi_c$$

$$\lambda_{10} = \frac{\mu_1}{\mu_1 + \mu_2 \eta} \geq \Omega$$

$$0 \leq F \leq F_{\text{max}}$$
3.2.4.1 Results

In this Section two important results from the manager’s optimization problem are analysed. From the results compliance profit, $\pi_c$, and compliance rate, $\Omega$ can be stated as:

\[
\pi_c = \pi_{2v} - \mu_2 F + \frac{\beta \mu_2 \eta [\pi_{2v} - \pi_{1c} + \mu_1 F - \mu_2 F]}{1 - \beta (1 - \mu_1)} \tag{3.13}
\]

and

\[
\Omega = \frac{\mu_1}{\mu_1 + \mu_2 \eta} \tag{3.14}
\]

Equation (3.13) shows that at the optimum the leverage, $L_1 = \pi_c$. Thus, the punishment $F$, should be chosen in such a way that it should not be profitable to violate. In other words, $F$ should be such that gains from violation should not exceed gains from compliance. Equation (3.14) shows that compliance rate is solely determined by group inspection probabilities $\mu_1$ and $\mu_2$, and the transition probability $\eta$. One implication of this is that compliance rate, $\Omega$, rises when inspection probability in group 1, $\mu_1$, together with transition probability $\eta$, are increased while reducing inspection probability in group 2, $\mu_2$, simultaneously. In other words, compliance at the optimum is increased by reducing inspection in $G_2$. To illustrate this let us look at a simple example. Increasing both $\mu_1$ and $\eta$, from 0.25 to 0.5 each, and reducing $\mu_2$ from 0.75 to 0.5, simultaneously, raises compliance rate from about 0.57 to approximately 0.67. Recall that $\mu_1 + \mu_2 = 1$, and $\eta \leq 1$. A possible explanation to this is that when transition probability $\eta$ is increased, firms in group 2 have the incentive to comply knowing that there is a high chance of being transferred to.
group 1, where inspection is low and therefore are able to cheat by violating. This means that in equilibrium the manager is better off doing the following: reducing the probability of inspection in group 2, increasing the probability of transfer from group 2 to group 1, and increasing inspection rate in group 1. Another implication of Equation (3.14) is that to try to minimize the average inspection rate, $\psi$, the fisheries manager does not achieve perfect compliance, that is, $\Omega \neq 1$. However, there is an extent to which $\mu_2$ can be reduced. This and other observations are examined next.

We examine the possibility of achieving perfect compliance as well as the extent of possible reduction of inspection probability, $\mu_2$, in group 2. First let Equation (3.9) be re-arranged as: $L_1 = \pi_{2v} - \mu_2 F + \frac{\beta \mu_2 \eta [\pi_{2v} - \mu_2 F] - (\pi_{1v} - \mu_1 F)}{1 - \beta (1 - \mu_1)}$. If in equilibrium maximum violation profits, $\pi_v^{max}$, in both groups are the same for all firms violating, as earlier indicated, and that from Equation (3.5), $\pi_{2v} - \mu_2 F = \pi_{1v} - \mu_1 F$, then the above relation implies $\pi_{2v} - \mu_2 F \leq L_1$. Given that $\beta \leq 1$, by setting $\beta = 1$, $L_1$ can be re-written as:

$$L_1 = \pi_{2v} - \mu_2 F + \frac{\mu_2 \eta (\pi_{2v} - \mu_2 F)}{\mu_1} - \frac{\mu_2 \eta (\pi_{1v} - \mu_1 F)}{\mu_1},$$

(3.15)

and

$$\pi_{2v} - \mu_2 F \leq [\pi_{2v} - \mu_2 F] \left(1 + \frac{\mu_2 \eta}{\mu_1}\right) - \frac{\mu_2 \eta (\pi_{1v} - \mu_1 F)}{\mu_1} = [\pi_{2v} - \mu_2 F] \left(\frac{\mu_1 + \mu_2 \eta}{\mu_1}\right) - \frac{\mu_2 \eta (\pi_{1v} - \mu_1 F)}{\mu_1}.$$

Let us recall that in steady-state the stationary probability of being in $G_2$, is:

$$\lambda_{10} = \frac{\mu_1}{\mu_1 + \mu_2 \eta}.$$  Then letting $\frac{\mu_1 + \mu_2 \eta}{\mu_1} = \frac{1}{\lambda_{10}}$, and $\lambda_{10} \geq \Omega$, the following is established:
\[ \pi_{2v} - \mu_2 F \leq \frac{\pi_{2v} - \mu_2 F}{\lambda_{10}} - \frac{\mu_2 \eta (\pi_{1v} - \mu_1 F)}{\mu_1} \leq \frac{\pi_{2v} - \mu_2 F}{\Omega} - \frac{\mu_2 \eta (\pi_{1v} - \mu_1 F)}{\mu_1} \]

\[ \iff \]

\[ \pi_2 - \mu_2 F \leq \frac{\pi_{2v} - \mu_2 F}{\lambda_{10}} \leq \frac{\pi_{2v} - \mu_2 F}{\Omega}. \quad (3.16) \]

From here the following important results are established.

**Result 1:** Inspection has lower bound.

**Result 2:** Optimum compliance cannot be perfect.

**Proof of Result 1.**

Let \((\pi_{2v} - \mu_2 F)\Omega \leq \pi_{2v} - \mu_2 F\) and \(\pi_{2v}(\Omega - 1) \leq \mu_2 F(\Omega - 1)\), yielding \(\mu_2 \geq \frac{\pi_{2v}}{F}\).

For \(\pi_{2v} = \pi_{v}^{max}\), \(F = F^{max}\), and \(\pi_{v}^{max} < F^{max}\), observe that \(\mu_2 \geq \frac{\pi_{v}^{max}}{F^{max}}\). This means that inspection in \(G_2\), at the optimum is greater than or equal to \(\frac{\pi_{v}^{max}}{F^{max}}\), and cannot be set below \(\frac{\pi_{v}^{max}}{F^{max}}\). Recalling that \(\mu_2 = (0, 1]\), notice that if \(\pi_{v}^{max} = F^{max}\), then \(\mu_2\) can only take on a minimum value of 0, thus proving Result 1.

The implication of Result 1 is that even though reducing inspection in group 2 in equilibrium is desirable (see earlier discussion in this section) beyond a given lower bound any further reduction in \(\mu_2\) is not optimal.

**Proof of Result 2.**
From Equation (3.16) let $(\pi_{2v} - \mu_2 \Gamma) \Omega \leq \pi_{2v} - \mu_2 \Gamma$. This implies that $\Omega \leq 1$. But, as earlier noted, if $\pi_v^{\text{max}} < \Gamma^{\text{max}}$, then $(\pi_v^{\text{max}} - \mu_2 \Gamma^{\text{max}}) \Omega < \pi_v^{\text{max}} - \mu_2 \Gamma^{\text{max}}$, yielding $\Omega < 1$. This shows that at the optimum compliance can not be perfect (i.e. $\Omega \neq 1$), satisfying Result 2.

Result 2 implies that even though management would expect to observe perfect compliance from all firms, compliance cannot be perfect in equilibrium. From Equation (3.14) observe that perfect compliance in equilibrium is achievable only if inspection of group 2 firms, $\mu_2$, and, or transition probability, $\eta$, are reduced to zero. As observed from Result 1, inspection of group 2 firms in equilibrium has a lower bound and so setting $\mu_2$ to zero is not optimal. In addition since the transition probability, $\eta$, is an incentive to induce firm compliance setting it to zero is costly.

We have discussed the interaction between the manager and the firms under different strategies, together with the transition movements. Next we investigate the possible consequence of these strategies and interactions in specific fisheries cases. In Section 3 we consider firms’ effort choices when complying or violating under different management regimes given management enforcement instrument in a single period. In this static case firm movements between groups, as an incentive instrument, do not apply; firms have inspection and punishment only. This is followed by analysis under a dynamic case in Section 4. In this scenario we consider the optimal equilibrium strategy, $S_{10}$, discussed in Section 2, again in a specific fisheries setting.

### 3.3 Firms’ Effort Choices when Complying or Violating: A Static Case

In this Section a single period, static case, is used to illustrate how illegal fishing and enforcement enter the standard fisheries model. Specifically, the Section exam-
ines the effect of illegal effort choices on harvest, profit, and stock levels in a single period, given inspection and punishment as enforcement instruments. Given the fisheries manager’s target levels, firms’ effort choices when either complying or violating in a single period will have varying effects on stock, harvest and profit levels. We consider the effect of firms’ effort choices on these variables when firms comply or violate in any single period. In this case, it is assumed all firms are in equilibrium, and are all either complying or violating. The effects of these choices are examined under individual fishing quota (IFQ or simply IQ) and maximum economic yield scenarios. We focus on the non-transferable individual quota management regime.

3.3.1 Effort choices under quota management regime when complying

Catch monitoring and reporting is argued to deserve more attention in current policy processes focused on establishing property rights. This emphasizes the argument that the model developed in this paper, though based on individual quota (IQ) management system, is applicable and important under various management systems in fisheries, as far as profit maximization, conservation, and sustainability issues are concerned.

It is important to investigate the firm’s behaviour, in terms of effort choices under non-transferable individual quota (IQ) management system. Under the IQ system we assume that in any given period a firm may choose to comply or violate a management policy on allowable quota. Theory shows that the private owner of the fishery would not allow effort to expand beyond maximum sustainable yield effort (Crutchfield and Zellner, 1962; Munro, 1992). It is, therefore, assumed in this Section that the manager is ‘naive’ and believes firms are not violating by
employing illegal effort to harvest more than allowed under IQ management system. ‘Naive’ here is used to describe the manager who believes there is no illegal activity or violations of the regulations, and therefore does no inspection. This assumption is relaxed later in Section 3.3.3. The maximum economic yield (MEY) case is, therefore, examined. Taking the first derivative of total revenue, TR, and total cost, TC, with respect to effort, the marginal revenue and marginal cost of the firms are defined. Expressing TR and TC respectively as \( TR = pqBE \), and \( TC = cE \), and making the necessary substitutions the partial derivatives of TR and TC with respect to effort, \( E \), are expressed as: \( \frac{\partial TR}{\partial E} = \frac{\partial TC}{\partial E} \), the equivalent of \( MR \) and \( MC \), respectively. This expression also implies that marginal revenue and marginal cost are equal, and expressed as: \( MR = MC \). The maximum economic yield effort and stock levels are also found to be:

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

and

\[
B_{MEY} = \frac{K}{2} \left( 1 + \frac{c}{pqK} \right),
\]

respectively. The maximum economic yield harvest and firms’ profit, given as:

\[
H_{MEY} = qB_{MEY}E_{MEY}
\]

and

\[
\pi_{MEY} = pH_{MEY} - cE_{MEY}
\]
after the necessary substitutions are derived as:

\[
H_{MEY} = \frac{rK}{4} \left[ 1 - \left( \frac{c}{pqK} \right)^2 \right]
\]  

(3.17)

and

\[
\pi_{MEY} = \frac{r}{4q} \left( \frac{(pqK - c)^2}{pqK} \right) = \frac{r}{4q} \left( \frac{r p K}{4} \right) \left[ 1 - \left( \frac{c}{pqK} \right)^2 \right],
\]  

(3.18)

respectively.

Observe from the \(E_{MEY}\), the \(H_{MEY}\), and the \(\pi_{MEY}\) expressions here that increases in cost reduce profits and so the profit maximizing firm reduces effort and, consequently harvest, in order not to reduce profits. The effect of this profit maximizing behaviour is that the biomass, \(B_{MEY}\), under maximum sustainable yield, increases as cost rises. Notice that under the IQ system profit is not zero. The manager expects the firms to ensure that rent continues to be positive.

### 3.3.2 Effect of effort choices when violating

In this Section we relax the earlier assumption of the manager being naive. We now assume that the manager believes firms may have incentives to employ illegal effort to increase harvest. The manager therefore uses inspection and punishment as incentive instruments to deter firms from violating. The consequences of such violation under IQ, specifically the effect of firms’ effort choices on harvest and stock levels, are studied.

Given that the profit motive may well account for the majority of violators, the focus of this paper, thus, is to investigate firms’ behaviour where rent-seeking is the
sole motivating factor when engaging in illegal harvesting. As before, groups 1 and 2 firms violating are denoted as ‘1v’ and ‘2v’ respectively. Recall that the fisheries manager inspects firms in these two groups with different inspection rates; that is, group 1 firms are inspected with $\mu_1$, while group 2 firms are inspected with $\mu_2$. These firms also receive different punishments when violating. For group 1 firms the punishment is $\mu_1 f h'$ and the chance of being moved to group 2, and for group 2 firms the punishment is $\mu_2 f h'$.

### 3.3.2.1 Group 1 firms’ choices when violating under maximum economic yield

In Section 2 we made the assumption that firms in both groups choose legal and illegal effort when violating. Given this assumption the firms maximize profit by choosing illegal effort, $E^{IL}$, subject to biomass being sustainable. We state the problem of group 1 firms violating, in a static case, and analyse the effect of the firms’ effort choices under maximum economic yield (MEY). Let the profit of group 1 firms violating be given by:

$$\max_{E^{IL}} \pi_{1v} = [(pqB - c)E^L + (pqB - c - \mu_1fqB)E^{IL}]$$

subject to

$$B = K\left(1 - \frac{q}{r}[E^L + E^{IL}]\right)$$

$$B \geq 0; \quad E^{IL} \geq 0$$

Taking the first order condition of Equation (3.19) with respect to illegal effort, $E^{IL}$, and re-arranging we find the static equilibrium level of illegal effort. Notice that we
take the first derivative with respect to illegal effort because firms are deliberately choosing illegal effort and so it is more interesting to analyse the effects of this choice. We establish the static equilibrium level of illegal effort as:

$$E^{IL}_{1v(MEY)} = \frac{r}{2q} \left[ 1 - \frac{c}{qK(p - \mu_1 f)} \right] - \frac{1}{2} \left[ \frac{p}{(p - \mu_1 f)} + 1 \right] E^{L}_{1v(MEY)}$$ (3.20)

Similarly, the illegal effort chosen by group 2 firms violating can also be expressed as:

$$E^{IL}_{2v(MEY)} = \frac{r}{2q} \left[ 1 - \frac{c}{qK(p - \mu_2 f)} \right] - \frac{1}{2} \left[ \frac{p}{(p - \mu_2 f)} + 1 \right] E^{L}_{2v(MEY)}$$ (3.21)

Here it can be observed that for firms in both groups punishment and cost are the most significant determinants of effort choices. We explain this below.

Starting with punishment. From Equations (3.20) and (3.21) notice that for firms in both groups violating as $\mu f \rightarrow p$, holding all else constant, $E^{IL}_{MEY} \rightarrow -\infty$. This is because the terms in the last brackets of the equations approach negative infinity as marginal punishment gets closer to marginal gains. The result is that legal effort, $E^{L}_{MEY}$, as a component of total effort increases infinitely. In other words, as illegal effort virtually disappears legal effort increases, which is a desirable outcome. It is worth noting, however, that it is not optimal for punishment to exceed marginal benefit. When punishment exceeds marginal benefit (i.e., when $\mu f > p$) illegal effort grows infinitely positive (i.e. $E^{L}_{MEY} \rightarrow +\infty$). This may well explain the earlier argument that firms making losses, for example, may continue to violate knowing that vessels and cheap labour can be easily replaced when caught and punished (Agnew and Barnes, 2004).
Next we look at the effect of cost. It can be observed from the first brackets in the two equations that as $\mu f \to p$, holding all else constant, the negative effect of cost, $c$, on illegal effort explodes, driving illegal effort down towards negative infinity. This can be interpreted to mean that as punishment wipes away any gains from illegal effort, cost of operations becomes so large that no illegal effort is chosen. Significant increases in the carrying capacity of the biomass, $K$, on the other hand, may increase illegal effort, all else being equal.

We analyse the maximum economic yield stock level, $B_{MEY}$, by substituting for $E_{MEY}^{IL}$ in the stock function, $B$, above and simplifying to obtain the following expression for the $MEY$ stock level for group 1 firms violating:

$$B_{1v(MEY)} = \frac{K}{2} \left[ \left( 1 + \frac{c}{qK[p - \mu_1 f]} \right) + \frac{1}{r} \left( \frac{pq}{p - \mu_1 f} - 1 \right) E_{1v(MEY)}^{L} \right] \quad (3.22)$$

Similarly for group 2 firms violating $MEY$ stock level can also be expressed as:

$$B_{2v(MEY)} = \frac{K}{2} \left[ \left( 1 + \frac{c}{qK[p - \mu_2 f]} \right) + \frac{1}{r} \left( \frac{pq}{p - \mu_2 f} - 1 \right) E_{2v(MEY)}^{L} \right] \quad (3.23)$$

It is clear that for a set amount of effort, $B_{MEY}$ is positively related to legal effort, $E_{MEY}^{L}$, and cost, $c$. Again, the effect of punishment here is similar to that discussed earlier. For both groups 1 and 2 firms violating, as $\mu f \to p$, $B_{MEY} \to +\infty$, significant increases in cost increases stock levels, monotonically. Further to that, observe that when punishment exceeds marginal benefit, that is, $\mu f > p$, the impact on stock levels is negative, emphasising the point made earlier that punishment should have upper bound. Expressing $MEY$ harvest level as $H_{MEY} = qB_{MEY} \left[ E_{MEY}^{L} + E_{MEY}^{IL} \right]$, it is easy to see that illegal effort increases harvest, holding all else constant. This further explains the reduction in stock levels.
with increases in illegal effort, $E_{MEY}^{IL}$.

### 3.4 Firms’ Effort Choices when Complying or Violating: A Dynamic Case

This Section evaluates the full dynamic model when firms are in equilibrium playing optimal strategies; violate in group 1 and then comply in group 2 (i.e., the $s_{10}$ strategy). In Section 3.2 it was observed that firms in this game have three optimal strategies; $s_{00}$, $s_{10}$, or $s_{11}$, that is, comply when in either group, violate when in group 1 and comply in group 2, or violate when in either group, respectively. In Section 2 it was also argued that strategies $s_{00}$ and $s_{11}$ do not present interesting cases for analysis. This is further confirmed by Sections 3, where it was shown that both groups 1 and 2 firms are likely to violate for one reason or another, and so there is no rational justification to expect that in reality all firms will comply. This means that though strategy $s_{00}$ may have interesting theoretical interpretation, firms’ effort choices may not present useful practical insights and so it is not pursued further. For strategy $s_{11}$, if it is obvious that firms are going to choose to violate in each state, then management’s solutions could be straightforward, though not necessarily simple.

A more interesting case from a practical perspective is the non-absorbing strategy, $s_{10}$. Firms adopt this optimal strategy because they know it is costly to violate when in $G_2$ where they face more frequent inspection and, as a result, larger expected punishment. It is optimal for firms to comply in $G_2$, and get promoted to $G_1$ where violation is less costly for them. This takes us to Section 3.4.1.

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13 See the derivation of all first order conditions and the algebra in this Section in Appendix A.4.
3.4.1 Maximum economic yield under strategy: violate, comply

We first analyse firms’ effort choices under maximum economic yield (MEY) when adopting the optimal strategy \( s_{10} \) in equilibrium. To do this we set up the firms’ problem, in equilibrium, using the firms’ equilibrium profit for strategy \( s_{10} \) (see Table 4), and substitute for compliance and violation profits when in group 1 (i.e., \( \pi_c \) and \( \pi_{1v} \), respectively). The the set up is as follows:

\[
\max_{E_{IL}} \pi_{10} = \frac{1}{A} \left[ (\beta + Q)[pqB - c]E^L + (pqB - c - \mu_1fqB)E^{IL}Q \right] \tag{3.24}
\]

subject to

\[
B = K \left( 1 - \frac{q}{\bar{q}}[E^L + E^{IL}] \right)
\]

\[
B \geq 0; \quad E^{IL} \geq 0,
\]

where; \( A = (1 - \beta)[1 - \beta(1 - \mu_1 - \mu_2\eta)] \), and \( Q = [1 - \beta(1 - \mu_1\eta)] \). From the set up we identify the respective total revenue (\( TR_{10} \)) and total cost (\( TC_{10} \)) as:

\[
TR_{10} = \frac{1}{A} \left[ \beta(pqB + qB)QE^L + (pqB)QE^{IL} \right]
\]

and

\[
TC_{10} = \frac{1}{A} \left[ (\beta + Q)cE^L + (c + \mu_1fqB)QE^{IL} \right].
\]

Substituting for the equilibrium stock, \( B \), we then take the respective first order conditions (FOCs) with respect to illegal effort, \( E^{IL} \), to obtain the equilibrium marginal revenue (\( MR \)) and marginal cost (\( MC \)), and solve for the illegal MEY.
effort, $E_{\text{IL}}^L$. We do so because firms adopting strategy $s_{10}$ in equilibrium choose illegal effort, taking legal effort, $E^L$, as given. When firms are adopting strategy $s_{10}$ choice of illegal effort presents a more compelling case for analysis. This is so because illegal effort has been shown earlier in Section 3 to have negative impact on both legal effort and stock levels. From the FOCs the level of illegal effort choice when firms adopt strategy $s_{10}$ is determined as:

$$E_{\text{IL}}^L = \frac{r}{2q} \left(1 - \frac{c}{qK(p - \mu_1 f)}\right) - \frac{1}{2} \left[1 + \frac{(\beta + Q)p}{Q(p - \mu_1 f)}\right] E_{\text{EL}}^L. \quad (3.25)$$

This equation shows the inverse relation between legal and illegal efforts under MEY. In other words, an increase in one leads to a decrease in the other, all else being equal.

The impact of punishment on illegal effort is also observed. It is clear from the above equation that as punishment, $\mu_1 f$, approaches marginal gains, $p$, legal MEY effort, $E_{\text{EL}}^L$, approaches infinity, and forces illegal MEY effort, $E_{\text{IL}}^L$, to approach negative infinity. If the last part of the right hand side of the Equation (3.25) is ignored, the strong impact of punishment on illegal effort is still observable. As punishment approaches marginal benefit, cost increases monotonically, and creates a strong and negative impact on illegal MEY effort, that is, as $\mu f \to p$, $c \to +\infty$, resulting in $E_{\text{IL}}^L \to -\infty$. So here, as in the case observed in Section 3.2, significant increases in cost and punishment reduce illegal effort significantly, with resulting positive impact on stock levels. This further confirms the earlier observation that marginal punishment should not exceed marginal gains/benefit, that is, $\mu_1 f \not\geq p$, since this only serves to increase illegal effort as observed in the Equation (3.25).

The consequences of firms’ profit maximization are examined next.
3.4.2  Profit maximization under strategy: violate, comply

This Section investigates the profit maximizing objective of the firm, over time, when; complying and violating. The outcome in each case is then compared with the Fisheries manager’s expectation as a benchmark. The discussion starts with the Fisheries manager.

3.4.2.1  No illegal fishing benchmark

In any given period the fisheries manager would expect that firms will choose only legal effort to maximize their profits. This means given a profit function of the form \( \pi_t = (pqB_t - c)E_t \), the manager’s objective function can be stated as:

\[
Max_{\{E_t\}_{t=0}} \int_0^\infty e^{-\delta t} \pi_t(B_t, E_t) dt \tag{3.26}
\]

subject to

\[
\dot{B}_t = r B_t \left( 1 - \frac{B_t}{K} \right) - qB_tE_t
\]

\[
B_t \geq 0; \quad E_t \geq 0
\]

where \( B_t \), the stock at time \( t \), is the state variable and \( E_t \), the effort at time \( t \), is the choice or control variable. Setting up the Hamiltonian and taking the FOCs, the
manager’s expected effort choice for all firms, $E^*$, in steady-state, and the modified golden rule ($MGR$) of the resource stock accumulation are respectively derived as:

$$E^* = \frac{r}{q} \left(1 - \frac{B^*}{K}\right)$$

and

$$\delta = r \left(1 - \frac{2B^*}{K}\right) + \frac{r}{n} \left(1 - \frac{B^*}{K}\right) \frac{c}{pqB^* - c}, \quad (3.27)$$

where $B^*$ is the stock level in steady-state.\(^{14}\) The $MGR$ is sometimes referred to as the economic return, at the margin, on investment in the resource. Notice that when $c = 0$, the social discount factor, $\delta$, is equal to the marginal return on the stock due to the growth function, i.e. $\delta = r \left(1 - \frac{2B^*}{K}\right) \equiv F'(B^*)$. This means it is worthwhile for the fisheries manager to ensure that sustainable harvest, at the margin, is equal to the social discount factor. On the other hand, when $\delta = 0$, it can be observed that $F'(B^*) < 0$, i.e. a situation where the marginal product of the Fishery resource is negative. Next, we analyse firms’ profit maximizing behaviour as a case of IUU.

### 3.4.2.2 Firms’ behaviour under violation

From earlier discussions, it has been noted that firms undertaking illegal unreported and unregulated (IUU) activities are violating a regulation or set of regulations. It was further indicated that firms do so by employing illegal effort, $e_t^{IL}$ at any time, $t$. In Section 2 it was established that one interesting equilibrium behaviour of the firm is to choose strategy $s_{10}$. This discussion is continued here by examining the firm’s

\(^{14}\)See proof in Appendix A.5.
profit maximizing behaviour when adopting this strategy in any given period. As before, \( N \) competing firms in the fishery at time \( t \) are considered. A firm choosing strategy \( s_{10} \) chooses illegal effort, \( e_{iL} \), over and above the legal effort, \( e_{iL} \). The firm in this case faces a possible punishment of magnitude, \( \mu_1 f q B_t e_{iL} \). The firm’s profit function can then be expressed as: \( \pi_t = pq B_t (e_{iL} + e_{iL}^{IL}) - c(e_{iL} + e_{iL}^{IL}) - \mu_1 f q B_t e_{iL}^{IL} \).

Firm \( i \) optimizes its profit, taking into account effort choices of its competitors. Defining \( e_{iL} + e_{iL}^{IL} \equiv e_{iT} \) as a firm’s total effort at time \( t \), firm \( i \)’s profit maximizing behaviour is characterized by the following optimization problem:

\[
\text{Max } \{ \sum_{t=0}^{\infty} e^{-\delta t} \left\{ pq B_t e_{iT} - c e_{iT} - \mu_1 f q B_t (e_{iT} - e_{iL}) \right\} \} \ dt
\]  

(3.28)

subject to

\[
\dot{B}_t = r B_t \left( 1 - \frac{B_t}{K} \right) - q B_t e_{iT} - \sum_{j \neq 1} q_t B_t e_{jt}^{T} \]

\[ B_t \geq 0; \quad e_{iT}^{T} \geq 0 \]

Again, assuming all \( j \) other firms to be identical, making the necessary assumptions, and taking the FOCs of the Hamiltonian gives the firm’s steady-state effort choices and the MGR, when violating, respectively as:

\[
e_{iT} = \frac{r}{n q} \left( 1 - \frac{B}{K} \right)
\]

and

\[
\delta = r \left( 1 - \frac{2B}{K} \right) - \frac{r}{n} \left( 1 - \frac{B}{K} \right) \left[ \frac{q(n - 1)(p - \mu_1 f) \overline{B} - nc}{q \overline{B}(p - \mu_1 f) - c} - \frac{q^2 \overline{B} \mu_1 f e_{iL}^{IL}}{q \overline{B}(p - \mu_1 f) - c} \right]
\]

(3.29)
In this case when \( c = 0 \), \( \delta = \frac{r}{n} \left[ 1 - (n + 1) \frac{\overline{B}}{K} \right] + \frac{\mu_1 q f \bar{e}^{IL}}{p - \mu_1 f} \). This is to say that the discount factor increases by the level of illegal activities in the fishery. This means IUU activities place less value on the future of the fishery. Firms violating are impatient, and by their activities reduce the biomass, \( \overline{B} \), in equilibrium, thereby eroding any investment in the fishery. This is emphasized even when \( \delta = 0 \). When \( \delta = 0 \),

\[
\begin{align*}
 r \left( 1 - \frac{2\overline{B}}{K} \right) &= \frac{r}{n} \left( 1 - \frac{\overline{B}}{K} \right) \left[ \frac{q(n - 1)(p - \mu_1 f)\overline{B} - nc}{q\overline{B}(p - \mu_1 f) - c} - \frac{q^2\overline{B}\mu f e^{IL}}{q\overline{B}(p - \mu_1 f) - c} \right],
\end{align*}
\]

(3.30)

showing that marginal product of the fishery is eroded mainly by the consequences of firms’ illegal behaviour when adopting strategy \( s_{10} \) to maximize economic rent. Possible reasons accounting for illegal behaviour have been discussed earlier. It is, however, important to emphasise that another plausible reason for such myopic behaviour among IQ owners could be the lack of permanent ownership rights under the system. In other words, the lack of transferability rights under the IQ system could be disincentive to preserve the stock, and not to discount the future heavily, particularly for retiring fishers or firms planning to leave the fishery. This echoes views expressed by Arnason (1990) and Grafton (1996). In the case of ITQ, however, the greed factor mentioned earlier could be a major reason for engaging in illegal activities that are likely to erode any future benefits that may accrue from increases in stock levels. This also confirms the assertion of Nowlis and Van Benthem (2012) that the belief that ITQ management systems prevent fisheries collapse may not be entirely correct.

\[15\text{See proof in of Appendix A.5.}\]
3.5 Concluding Remarks

Destructive and illegal fishing activities are found to be a major threat to conservation and sustainability of the fisheries industry. Activities such as discard, the use of explosives, exceeding allowable quotas, unauthorized by-catch, and others, violate fisheries regulatory measures and are therefore considered illegal. Such illegal, unreported, and unregulated (IUU) fishing activities have been shown to contribute to underestimation of catch and effort. IUU fishing undermines management programs, affect fish habitat, and is an inherently unsustainable fishing practice. This Chapter sought to investigate the strategic interaction between fishers and management in the presence of IUU, and the possible effect of such interaction on the fish biomass.

We used a game theoretic approach to examine the firm’s choice of legal and illegal effort to maximize profit in response to the fisheries manager’s choice of regulation, in the form of harvest quota, and enforcement as; fines, inspection probabilities, and group classification. The interaction between fishers and management was modeled as a two-person dynamic game which gives rise to a steady-state equilibrium. This equilibrium characterized the less-than-perfect enforcement strategy of the manager in response to the firms’ compliance and violation behaviour. In addition, the interaction allowed consideration of the dynamic effect on fish stocks. To effectively analyse the effect of firms’ effort choices on stock levels, it was important to understand why even firms that regularly comply may choose to violate at one time or the other. We assumed rent-seeking behaviour as the main motivation for violation, and that any illegal effort increased catch levels above the allowable quota and consequently impacted the biomass negatively.

Results show that optimal compliance cannot be perfect, and that inspection has a lower bound. Even though management would expect to observe perfect compliance...
from all firms, compliance cannot be perfect in equilibrium. To achieve perfect compliance in equilibrium would require reducing the inspection of group 2 firms or the transition probability of a group 2 firm to group 1 to zero. Inspection of group 2 firms in equilibrium was shown to have a lower bound and so setting it to zero in equilibrium is not optimal. In other words, even though reducing inspection of group 2 firms in equilibrium was shown to increase compliance, beyond a given lower bound any further reduction in inspection of group 2 firms is not optimal as it is excessively costly to do so. Increasing the transition probability, on the other hand, was shown to increase compliance and so setting the transition probability to zero is also costly.

Furthermore, contrary to empirical evidence suggesting that maximum penalties be increased considerably (Ostrom, 1990), the theoretical results in this paper indicate that punishment should have an upper bound if it is to achieve the purpose for which it is intended. Results show that marginal punishment should not exceed the marginal gains, since this only serves to increase illegal effort, with a corresponding negative impact on the fish biomass. Le Gallic and Cox (2006), emphasizes that even corrective measures carry a cost and, thus, care must be taken to establish the benefit of respective corrective measures. This view is supported by existing theory in the literature (De Merode et al., 2007). IUU activities are found in this paper to place less value on the future of the fishery by using a discount factor higher than that which will ensure sustainable harvest over time. Our analysis show that firms violating discount the future heavily, thereby eroding any investment in the fishery.

This Chapter argued that a plausible reason for illegal behaviour even among quota owners could be the lack of permanent ownership rights under the quota system. The lack of transferability rights under the quota system could be disincentive to preserve the stock, and not to discount the future heavily, particularly for retiring
fishers or firms planning to leave the fishery. This argument is supported by views earlier expressed by Arnason (1990). In the case of ITQ, however, the greed factor identified in this paper could be a major reason for engaging in illegal activities that are likely to erode any future benefits that may accrue from increases in stock levels. The paper confirms earlier theoretical suggestions that economic incentives may be sound economic policies to discourage illegal fishing (Costello and Guinness, 2010). Such incentives may include increasing operational and capital costs, subsidy removal, increasing the cost of engaging in illegal activities through punishment, as well as increasing the risk of engaging in illegal fishing activities.

Previous studies show that enforcement is costly and deterrence model alone does not adequately explain violation tendencies (De Merode et al., 2007). This implies that other economic incentives are required to complement the role of punishment, cost, and risk, as measures to correct illegal operations in the fisheries. The literature suggests that a management tool that may lower firms’ incentive to engage in illegal activities is the effective enforcement of domestic management regimes. Domestic management regimes that are well designed and effectively enforced to ensure higher incomes for fishers are identified as an effective policy to lower firms’ incentive to engage in illegal fishing (Ostrom, 1990). It is also argued that domestic fisheries generating higher incomes have a lower incentive to engage in IUU activities (Kuperan and Sutinen, 1998; Sutinen and Kuperan, 1999). This means that the effective enforcement of well-designed domestic management regimes, an important determinant of the income of domestic fishers, can lead to a significant reduction in IUU activities.

The application of game theoretic concepts to analyse illegal activities in fisheries, as shown in this Chapter, is innovative. It is a unique approach to understanding the complex interactions between management and firms in the fishery industry.
The approach is simple but provides insightful results that can guide policy in the quest to address the IUU problem and to conserve and sustain fish stocks across time. Applying this method to find plausible solutions to management challenges in internationally shared fishery is an interesting extension we investigate in future work. In addition, the assumption that the probability of inspection is not affected by the incidence of violation is an equally interesting case we investigate in the future.
Chapter 4

Evaluating Profit Efficiency of the South Australian Rock Lobster Fishery: Nerlovian and Directional Distance Function Approach

4.1 Introduction

The South Australian Rock Lobster Fishery comprises of the Northern and Southern Zone fisheries. The fishery is the most valuable in the state’s commercial fishing industry. Between 1997/98 and 2008/09 the export value of rock lobster from the state was, on average, about $88 million per annum. In the 2008/09 fishing period, the fishery contributed nearly 41% of all fisheries’ contribution to South Australia’s gross state product (GSP). The rock lobster fishery’s contributions to employment and household income in the state’s fishery sector were 36% and 39%, respectively, in the 2008/09 period. Economic and biological sustainability of the fishery is, therefore, important to both managers and firms in the sector.

Issues confronting this valuable sector of the state’s economy include falling biomass levels, as well as economic challenges. Between 1997/98 and 2009/10 fishing periods,
the sector registered 26% and 67% declines in catch levels in the Southern and Northern Zones, respectively. The fall in catch is attributed to significant and persistent reductions in stock levels over the period. At the same time the average harvest cost has been on the increase in both fisheries. For example, cost per kilogram of harvest increased by about 97% in the Southern Zone, with harvest cost in the Northern Zone registering a 128% increase. These challenges have meant that profit in the fishery has seen significant fluctuations over the same period.\(^1\) Though costs in both fisheries have been on the increase, profits in the Southern fishery are persistently higher than in the Northern fishery. As a result the Southern fishery is considered more profitable and therefore more efficient. However, it is possibly the case that the Southern fishery is not achieving maximum profits given its cost structure and technology and therefore not profit efficient.

Significant fluctuations in stock and profit levels, the importance of the fishery to the state’s economy and, therefore, the need to understand the future of the fishery, show that there is compelling need for critical evaluation of the sector’s economic performance.

This Chapter uses the Nerlovian and Directional Distance Function approach to analyze profit efficiency in the fishery. In the context of fisheries the application of the Nerlovian and Distance function methods is new. Advantages of this method are that it has decomposition power as well as the ability to handle negative profits. There are a number of studies done in the past on the South Australian Rock Lobster Fishery.\(^2\) However, to our knowledge there are no studies of profit efficiency and hence none that have employed the Nerlovian and Directional Distance

\(^{1}\) All figures are summaries of figures obtained from EconSearch, 2011. The export value is free-on-board (fob) value. We are extremely grateful to EconSearch, particularly Dr. Julian Morison (Director, EconSearch), for making this firm level data available to us. EconSearch is a research body established in 1995 to provide economic research and consulting services in agricultural and resource industries throughout Australia (EconSearch, 2011). EconSearch collects the confidential data and provides reports to the state fisheries regulator, PIRSA.

\(^{2}\) See for example: McGarvey and Prescott (1998); McGarvey and Matthews (2001); EconSearch (2011); Punt et al. (2012).
Function techniques in this Fishery. Existing investigations are analysis of annual profit levels in the Fishery. These investigations have consistently shown higher profit levels in the Southern Zone Fishery (EconSearch). The Chapter also tests if indeed the Southern fishery is more profit efficient compared to its Northern counterpart. The study includes four fishing years in the period 1997 to 2008, for which data are available. This period covers two management systems in the fishery: the total allowable commercial catch (TACC) and the individual transferable quota (ITQ) management systems. This makes it possible to compare the pre- and post-management changes and any possible effects on profit efficiencies. In Chapters 2 and 3 the differences between transferable and non-transferable quotas were explained. To compare the economic performance of the Northern and Southern fisheries, we make the necessary assumptions and carry out a meta-frontier analysis.

We show that though operational cost in the Southern Zone is lower than in the Northern Zone, on average the Northern Zone appears to be a little more profit efficient than the Southern Zone. The average total variable cost in the Northern Zone ranged between $171,805 and $247,108 for the 1997/98 to 2007/08 fishing period. For the same period the average total variable cost in the Southern Zone was between $124,583 and $216,047. For the same period, however, profit efficiency in the Northern Zone was between 59 - 78%, on average, with the Southern Zone registering profit efficiency levels of 53 - 77%, on average. This result further confirms evidence in the literature indicating that contrary to expectations a firm’s cost efficiency may not necessarily explain its performance in terms of profit efficiency (Berger and Mester, 1997).

Efficiency analysis helps decision makers identify sources of inefficiency in their management units. Profit efficiency evaluation is a valuable exercise that helps

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3 In Subsection 4.6.2 we test whether these efficiency measures are significantly different, and show that they are indeed statistically different. See detailed analysis in Section 4.6.
to tease out inefficiencies that result from choosing suboptimal input-output mix. Technical challenges of measurement and decomposition of profit inefficiency have often overshadowed the relevance of profit efficiency analysis in fisheries. This difficulty, to a large extent, explains the relatively small number of empirical studies on profit efficiency even in the banking sector (Resende and Silva, 2007). In fisheries Fox et al. (2003), Dupont et al. (2005), and others use index number techniques to examine profit efficiency. In the past efficiency studies in fisheries have focused on productivity, technical, cost, and in some instances, revenue and profit analysis. We discuss details later in the Section. Attention to profit efficiency analysis has been minimal compared to cost. The presence of huge subsidies in fisheries, including state contributions the world over (Sumaila et al., 2010), may make even failing fishing firms appear efficient when the emphasis is placed on cost efficiency measures alone. Input subsidies may mask real input costs thereby reducing the full impact of input cost on maximum attainable profit.

Profit efficiency is found to account for errors on both the output and input sides. Evidence suggests that inefficiencies on output side may be as large or larger than inefficiencies on the input side (Berger et al., 1993). This has led to the assertion that the profit efficiency concept is superior to that of cost efficiency when evaluating overall firm performance. Further to that, it has been shown that while productivity gains may have the potential to contribute to increase in profit, changes in other factors such as changes in output and input prices can as well affect profitability.\textsuperscript{4} The literature points out that the omission of the revenue side, under cost measurement, may introduce significant empirical distortions. Resende and Silva (2007) cite Maudos and Pastor (2003) to point out why the omission of revenue in cost analysis is a problem. Inefficiencies resulting from suboptimal choice of input-output mix constitute a wider source of information and, therefore, presents a more

\textsuperscript{4}See Berger and Mester (1997) on the superiority of the profit efficiency concept. For the effect of factor and output price changes on profitability see Kompas et al. (2009)
accurate picture of efficiency levels in decision making units (Anderson et al., 2000). Furthermore, compared to cost, profit efficiency combines both cost and revenues in the analysis of technical and allocative efficiencies (Pasiouras et al., 2009). Currently the volume of studies on efficiency in fisheries is large but few (Fox et al. (2003), and Dupont et al. (2005), for example) specifically examine profit efficiency. Nerlove (1965) is credited for the introduction of the profit efficiency notion. The Nerlovian idea is to decompose profit by maximizing the profit of a given production function and finding the maximum profit (Färe and Grosskopf, 2000). The Nerlovian approach assumes firm price-taking behaviour and gives an indication of profit losses due to suboptimal choice of the input-output mix. Nerlove’s application was in the context of parametric estimation of production functions. Nonetheless, Banker and Maindiratta (1988), and later Färe and Grosskopf (1995) have demonstrated that the non-parametric approach to profit efficiency computation can well rely on the established Nerlovian theoretical concepts. The Nerlovian measure is well defined for zero and negative profits. The decomposition power is attributed to the Chambers et al. (1998a) formulation. This property, it is believed, accounts for its popularity in recent times (Cherchye et al., 2008). It is, however, important to note that the Nerlovian measure is not without shortcomings. For instance, the measure requires inputs and outputs to be strictly positive. This requirement could be too restrictive and may pose significant challenges when dealing with multiple outputs in a multi-species fishery. In other words, when a species is not harvested in a particular period the method can become inefficient. Another major drawback of the Chambers et al. (1998b) formulation is the choice of normalization and its economic interpretation.\footnote{The choice of normalization and its economic interpretation challenges remain unresolved. For details see Nowlis and Van Benthem(1998).} The disadvantages notwithstanding, the Nerlovian method presents a huge advantage over a number of other methods currently used in profit efficiency analysis.
Consensus on the most appropriate technique for profit efficiency is yet to be achieved despite several techniques proposed in the past (Resende and Silva, 2007). In fisheries the introduction of the index number profit decomposition (INPD) method has proved to be an important tool for analyzing firm performance. The decomposition of profit helps to distinguish the economic impact of management decisions from all other factors that influence profitability in fisheries. Parametric and non-parametric techniques have also been used to analyze efficiency measures in fisheries, including profitability. Studies employing these methods in fisheries include Kirkley et al., 2002; Fox et al., 2003; Dupont et al., 2005; Grafton et al., 2006; and others. For details on INPD in fisheries see Fox et al.(2003), Sharp et al. (2004), and McWhinnie (2006). Both methods provide valuable insights for researchers and managers in the industry. However, the stochastic frontier, a parametric method, has been found not to be flexible when it comes to profit decomposition (Fox et al., 2003). In addition the small number of our observations do not make the application of stochastic frontier relevant in this case.

Despite its decomposition power the inability of the INPD method to overcome the negative profit problem remains a setback, particularly in fisheries where negative profits are not a rare phenomenon. For example, Färe and Grosskopf (2000) show that the additive structure of the profit function makes the radial Shephard type distance functions less appropriate dual model of technology for profit efficiency analysis. With the Shephard type radial input or output distance function efficiency can only be improved by altering all factors in the same direction. The Directional Distance Function, on the other hand, allows factors to change in opposite directions (Färe and Grosskopf, 2000). In other words, the Directional Distance Function allows distances to the frontier to be measured by simultaneous output expansion and input contraction (Nahm and Vu, 2013). In addition recent theoretical developments have focused on directional distance function techniques, with
empirical application of these methods gaining more prominence. For further de-
tails on theoretical and empirical discussions, see Chambers et al., 1998; Färe et al.,

The rest of the Chapter is organized as follows. Section 4.2 gives background
details of the South Australian Rock Lobster Fishery. In Sections 4.3 and 4.4 the
theoretical details of the Nerlovian, Directional Distance and meta-frontier methods
employed in this Chapter are explained. Section 4.5 describes the data and how
it was organized for use. In Section 4.6 the empirical application of the methods
are fully explained and detailed analysis of the results are provided. Section 4.7
concludes that the Nerlovian method possesses computational advantage when it
comes to negative profits, and gives future directions.

4.2 The South Australian Rock Lobster Fishery

The rock lobster fishery in South Australia is a state managed fishery. The fishery is
the most valuable commercial fishery in the state. Being a state managed institution
the fishery operates in accordance with management plans that fit into the primary
management objectives (EconSearch, 2011). The fishery is separated into two zones;
the Southern and Northern Zones. The separation of the fishery into the two zones
was in recognition of the significant differences in both geological and ecological
characteristics between the eastern and the western borders of the South Australian
coasts where these fisheries are located. Whereas the geological and ecological
structures of the Northern Zone afford less habitat for rock lobster species, the
features in the Southern Zone, on the other hand, support higher densities of rock
lobster (*Jasus edwardsii*). The Southern Zone with a coastline stretch of about
425km is more productive than its northern counterpart, which has a coastline
stretch in excess of 3700km (PIRSA, 2012). Both zones are further divided into regions, also known as marine fishing areas (MFAs). These MFAs demonstrate significant variations in catch and effort.

The Northern Zone is divided into four regions, with the Southern Zone having three divisions. The large scale Northern Zone rock lobster (NZRL) fishery operates across an extensive coastline. The fishery stretches from the mouth of the Murray river to the Western Australian border in the Great Australian Bight and waters around the Kangaroo Island. The ecosystem supporting the Northern Zone rock lobster fishery is characterized by patchy reef formations with large expanse of sandy bottom. Environmental changes, coupled with the unique ecosystem characterization, results in unstable recruitment to the fishery (PIRSA, 2012). Vessels in the Northern Zone operate a one to ten days fishing per trip, with the Southern Zone operating a day fishery with vessels fishing close to their home port (PIRSA, 2012). Fishing cost is found to be higher in the Northern Zone than in the Southern Zone due to the relatively longer distances traveled in the Northern Zone (EconSearch, 2011).

The Southern Zone Rock Lobster (SZRL) fishery operates as a large scale fishery, extending across a long coastline, from the mouth of the Murray river to the Victorian border. Unlike the NZRL fishery, the habitat for the species in these waters is suitable for recruitment. The SZRL, like the Northern fishery, is a single species, single method fishery, based on the harvest of southern rock lobster (*Jasus edwardsii*). Compared to the NZRL, fishing costs in the SZRL fishery are generally lower (PIRSA, 2012). The short distance fishing day trip method of the SZRL largely explains the relatively lower fishing costs in this fishery. The geological, ecological, and environmental characteristics of the SZRL fishery provide suitable habitat for

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6PIRSA: Primary Industries and Regions SA is the Government of South Australia’s development agency responsible for research and policy development for the state’s resources and industries.
the fishery. These characteristics significantly contribute to high densities of the SZRL fishery. Figure B.1, in Appendix B, shows the boundaries of the Northern and Southern Zone fisheries with their respective regional or marine fishing areas.

In the period 1997 to 2011, available figures show significant fluctuations in harvest levels in the Northern Zone. These fluctuations are attributed to a number of factors including pot reductions and reductions in the number of fishing days in the fishery (EconSearch, 2011). Reductions in the total allowable commercial catch (TACC) since the introduction of quota management system in 2003/2004 fishing period, is also cited as a contributing factor to the fluctuations in harvest levels. Prior to 2003 only the Southern Zone Rock Lobster (SZRL) fishery operated under TACC management system, with effort control, including seasonal closures to protect spawning females and conserve egg production. Quota management system was introduced in the Southern Zone in the 1993/94 period with subsequent TACC adjustments to account for falling biomass recruitment levels. However, it was not until 2003/04 when quota management system was introduced in the Northern Zone with TACC adjustments. Between 1997 and 2002 the Northern Zone was under various effort control management strategies. These strategies included flexible time closure, increase in size limit, and effort reduction. Since the introduction of the quota system, the main management strategy to ensure sustainability remains output control. Figure 4.1, below, shows changes in harvest and TACC levels over the period, 1997 to 2011. The TACC components of Figure 4.1 show the start of quota management systems in both fisheries. The quota system has full transferable rights. The fisheries are managed through output controls. The objective of this management strategy is to align harvest capacity with the biomass levels to ensure stock recovery and sustainability.
Figure 4.1: TACC and Harvest levels in the South Australian Rock Lobster Fishery between 1991 and 2011. Source: SARDI, 2012

From Figure 4.1, it can be observed that whereas TACC and harvest levels in the Southern Zone remained fairly stable until 2002, the Northern Zone experienced persistent declines over the period. It is also observable that TACC levels in the Northern Zone, since the introduction of the quota system in 2003, were constantly adjusted downwards. In the case of the Southern Zone TACC levels remained constant until the 2007/2008 period when it started experiencing constant declines. The TACC adjustments strategy is a management plan aimed at ensuring stable maximum economic returns for the commercial fisheries. Fluctuations in catch levels coupled with exchange rate changes have meant that profits have not been stable over the period. As explained later in this chapter products from these

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7 SARDI is the South Australian Government’s principal research institute, a division of PIRSA (see SARDI, 2012).
fisheries are mainly for exports, with about 80 percent going to the Japanese market (EconSearch (2011)). This makes exchange rate fluctuations an important factor in profits of the fisheries. Figures 4.2 and 4.3 show the fluctuations in both harvest and equity profit values between 1990 and 2008. Observe that the negative impact of fluctuations in catch seriously affect earnings in both Zones, with the Northern Zone suffering the greatest impact, particularly in the 2003/2004 fishing period.

![South Australian Rock Lobster Fishery: Harvest Value (1990/91 to 2007/08)](image)

Figure 4.2: Harvest values of the South Australian Fishery: 1991 – 2008
Source: SARDI, 2009

Some of the precautionary management approach outlined in the 2007 - 2010 ‘Management Plan’ of the Northern and Southern fisheries include; prior identification of undesirable outcomes and corresponding avoidance and corrective measures (PIRSA, 2012). Profit efficiency analysis fits well into this management frame. The decomposition of profit into technical and allocative efficiencies allows for the iden-
tification of challenges in the fishing and helps suggest corrective and avoidance measures.

Figure 4.3: Boat Profit at Equity for Northern and Southern Zones: 1997 – 2008

Source: SARDI, 2009

4.3 Methods

This Chapter employs the Nerlovian profit efficiency and Directional Distance Function techniques to analyze profit efficiency of the South Australian Rock Lobster Fishery. We do this by first computing the profit efficiency measure, then decompose it into technical and allocative efficiency components. To obtain the profit efficiency measure the maximum attainable profit is first computed using the data envelopment technique. We express the profit efficiency index as two components;
the technical and allocative indexes. The technical component is defined by the directional distance function. The firm’s maximal profit given the directional distance function establishes the duality between the price dual and quantity primal. In Section 4.3.2 we explain how this duality is established.

Data envelopment analysis (DEA) is a linear programming technique proposed by Charnes et al. (1978). The technique is used to determine the efficiency of a group of decision-making units relative to an efficient frontier (the envelope) by optimal input and output weights. A review of 196 studies assessing bank performance found that profit efficiency measures using DEA is rather limited (Fethi and Pasiouras, 2010). We focus on fishing firms’ profit maximization and define the Nerlovian profit efficiency measure as introduced by Chambers et al. (1998b). Given the production technology the maximum attainable profit is obtained by choosing the optimal input and output vectors. These vectors are established using the linear programming problem explained in the next Section.

4.3.1 Nerlovian profit efficiency measure

Nerlove (1965) first proposed the ratio and the additive measures of profit efficiency. The ratio measure considered profit efficiency in proportionate terms, with the additive measure expressing efficiency due to profit loss in monetary terms (see Cherchye et al., 2008). Chambers et al. (1998b) propose a version of the Nerlovian measures that normalizes profits using input and output price vectors. This way the Nerlovian profit efficiency index is expressed as two components; the technical and allocative (Färe et al., 2008). The Chambers et al. (1998b) formulation is adopted in this Chapter. The Nerlovian profit efficiency measure (NE) for each firm $k$, is
The Nerlovian measure is the normalized deviations between the maximum attainable profit and the firm’s observed (actual) profit. In this expression $\pi^*(p, w)$ is the maximum attainable profit, and $\pi^k(p, w)$ the observed profit of firm $k$. The vectors $p = (p_1, \ldots, p_M) \in \mathbb{R}^N_+$ and $w = (w_1, \ldots, w_N) \in \mathbb{R}^M_+$ are, respectively, the output and input price vectors. The vectors $g_x \in \mathbb{R}^N_+$ and $g_y \in \mathbb{R}^M_+$ are the directional vectors normalizing the profits. The direction $(pg_y + wg_x)$ is the value of the normalization. It must be noted that the Nerlovian measure assumes price-taking behaviour and gives an indication of profit losses due to sub-optimal choice of the input-output mix. The above definition of the Nerlovian measure implies that zero and negative profits pose no computational problems. This formulation also means that a fishing firm $k$, is fully profit efficient if and only if it achieves maximum profit, i.e. $\pi^k(p, w) = \pi^*(p, w)$. This implies that $NE$ is equal to zero when a firm is fully efficient. Profit inefficiency is identified whenever $NE$ is greater than zero. In other words, the level of a firm’s efficiency (inefficiency) is higher (lower) the closer its $NE$ measure is to zero. Taking $k = 1, \ldots, K$ fishing firms as the decision-making units, given technology $T$, it is supposed that each firm $k$ chooses strictly positive input and output vectors; $x = (x_1, \ldots, x_n) \in \mathbb{R}^N_+$ and $y = (y_1, \ldots, y_m) \in \mathbb{R}^M_+$, respectively, to maximize profit. The production technology, $T$, is specified as:

$$T = \{ (x_k, y_k) : \text{input } x_k \in \mathbb{R}^N_+ \text{ can produce } y_m \in \mathbb{R}^M_+ \}.$$  

Thus $T$ is of the vector space $\mathbb{R}^{M \times N}_+$, i.e., $T \in \mathbb{R}^{M \times N}_+$. We follow the literature and make the following standard assumptions in this Chapter: 1. the technology
set, \( T \), is closed; 2. free disposability of inputs and outputs; it is possible to waste inputs, that is, for \((x, y) \in T\), \(x' \geq x\), and \(y' \leq y\), imply \((x', y') \in T\); 3. it is feasible to do nothing, that is, \((0, 0) \in T\); and 4. the technology, \( T \), is convex. Though theoretically if \((x, y) \in T\), and \( x = 0 \), then \( y = 0 \), that is, no output is produced if there are no inputs, this Chapter implicitly assumes that firm \( k \) chooses strictly positive input and output vectors. In practice the assumption is that a fishing firm chooses positive outputs to maximize profits.

Suppose the \( k^{th} \) fishing firm faces input price vector \( w = (w_1, \ldots, w_n) \) together with output price vector \( p = (p_1, \ldots, p_m) \), then the profit efficiencies can be estimated. Expressing the firm’s total revenue as:

\[
p_y = \sum_{m=1}^{M} p_m y_m; \quad m = 1, \ldots, M
\]  

(4.2)

and associated total cost as:

\[
w_x = \sum_{n=1}^{N} w_n x_n; \quad n = 1, \ldots, N,
\]  

(4.3)

the firm’s profit is then obtained as:

\[
p_y - w_x = \sum_{m=1}^{M} p_m y_m - \sum_{n=1}^{N} w_n x_n.
\]  

(4.4)

Firms seek to maximize this profit given the production technology set \( T \). The maximized profit can be expressed as:

\[
\pi^*(p, w) = \max \{p_y - w_x : (x, y) \in T\}
\]  

(4.5)

\[
= p_y^* - w x^*.
\]
with \((x^*, y^*)\) being the optimal input and output vectors that yield maximum profit at the given input and output price vectors \((w, p)\). The profit function \(\pi^*(p, w)\), satisfies all the usual assumptions of convexity and continuity, homogeneity and non-negative, non-increasing in \(w\) and non-decreasing in \(p\). For further details, see Färe and Grosskopf (2005). Solving the following linear programming (LP) problem, the maximum profit for the \(k^{th}\) fishing firm relative to the technology, can be computed.

The LP for firm \(k\)'s maximum attainable profit is specified as:

\[
\pi^k(p, w) = \max \sum_{m=1}^{M} p_k y_{km}^k - \sum_{n=1}^{N} w_n x_{kn}^k
\]  

subject to

\[
\sum_{k=1}^{K} z_k y_{km}^k \geq y_{mk}^*, \quad m = 1, \ldots, M
\]

\[
\sum_{k=1}^{K} z_k x_{kn}^k \leq x_{nk}^*, \quad n = 1, \ldots, N
\]

\[
\sum_{k=1}^{K} z_k = 1, \quad z_k \geq 0, \quad k = 1, \ldots, K
\]

Thus given the technology, the \(k^{th}\) fishing firm chooses inputs \((x_n)\) to maximize profits. Following the literature the intensity variables, \(z_k\), are restricted to unity, that is, \(\sum_{k=1}^{K} z_k = 1\). The convexity constraint in the above DEA (LP) program is given by \(\sum z_k = 1\), imposing a variable return to scale (VRS) technology. This ensures that an efficient fishing firm is compared to a fishing firm of similar size. Further, the imposition of VRS condition in the maximum profit model, introduced earlier in this Section, implies that perfect competition is not assumed. This also means
that maximum profit may be different from zero (Koutsomanoli-Filippaki et al., 2012). This is perfectly legitimate in our application since we consider fishing firms under the individual transferable quota (ITQ) management system, different from the perfect competition open access case. Having established the profit efficiency measure the next step is to decompose it into technical and allocative components. The decomposition is done using the directional distance function.

4.3.2 Directional distance function

The technical component of the Nerlovian measure is defined by the directional distance function. The directional distance function measures the distance from an input-output vector within a feasible technology frontier along a chosen directional vector. Färe and Grosskopf (2000) define the directional distance function (DDF) by assuming convexity and closedness of the production technology as conditions ensuring the duality between the DDF and the profit function. Following these assumptions we state the DDF on the technology as:

\[
\overrightarrow{D}(x, y; -g_x, g_y) = \sup \{\beta : (x - \beta g_x, y + \beta g_y) \in T\}. \tag{4.7}
\]

It is important to note that the DDF differs from the traditional Shephard type distance functions in a number of ways (Färe and Grosskopf, 2000). One major difference is the requirement that the DDF be associated with an explicit direction in which efficiency is measured. The specified directional vector, \( g = (-g_x, g_y) \), is the vector earlier defined. The DDF seeks for the greatest possible input contraction in the negative direction \((-g_x)\) in order to obtain the maximum attainable expansion of outputs in the positive direction \((g_y)\). Chambers et al. (1998b) and Färe and Grosskopf (2005) prove that this is true if and only if \((x, y) \in T\). By the
simultaneous input contraction and output expansion feature the DDF represents
the technical inefficiency of an input-output vector achieving maximal profit (Nahm
and Vu, 2013).

Before a graphical illustration of the function is given it is important to explain
the frontier concept. The frontier determines maximal output capacity of decision-
making units given input levels. The frontier is determined using DEA to establish
the maximum potential output for a given set of inputs, and it is primarily used
to estimate efficiency. The frontier can be described as an efficient envelopment
surface, enveloping the production of a set of decision-making units under a specified
technology. With the variable returns to scale (VRS) assumption, points lying
on the frontier define the envelope and are efficient, while points lying below the
frontier are not efficient. The envelopment surface and the efficient projection path
to the surface are the key constructs of the DEA model (Cherchye et al., 2008).
The projection path is determined by the model’s orientation, that is, whether it
is input or output orientation. For capacity estimation purposes in fisheries output
orientation has generally been estimated empirically (Pascoe et al., 2003). In this
Chapter, input orientation estimation is employed given the objective to examine
efficient utilization of inputs to maximize profits. The maximum profit line which
is also established by solving the linear programing function specified in Section 3.1
above depicts the maximum attainable profit that a firm can obtain given input
and output market price levels. A decision-making unit is profit efficient if its
output level is on the frontier and is tangent to the maximum profit line. A simple
illustration of the function is shown in Figure 4.4 below.
Figure 4.4: A simple illustration of the Directional Distance Function

Figure 4.4, gives a simple one-input, one-output illustration of DDF. It shows the direction, $g = (-g_x, g_y)$, in which firms $F_1$ and $F_3$ must contract the input, given technology $T$, in order to expand output and attain the maximum attainable and efficient profit of firm $F^*$. Firm $F^*$, being on that part of the frontier where it is tangent to the maximum attainable profit, $\pi^*(p, w)$, is fully efficient, both technically and allocatively. Firm $F_2$ on the other hand, lies on the frontier so is technically efficient, but it is not tangent to maximum profit so is not allocatively efficient and, therefore, not optimal for firm $F_3$ to try to achieve the level of efficiency associated with $F_2$.

Next we illustrate the DEA estimation of the distance function. Including all inputs and outputs as the constraint set, the distance function for the $k^{th}$ fishing firm is
estimated as:

$$
\overrightarrow{D_T}(x^k, y^k; -g_x, g_y) = \max_{\beta, z} \beta
$$

subject to

$$
\sum_{k=1}^{K} z^k y^k_m \geq y^*_m \beta g_y, \quad m = 1, \ldots, M
$$

$$
\sum_{k=1}^{K} z^k y^k_m \leq x^*_n - \beta g_x, \quad n = 1, \ldots, N
$$

$$
\sum_{k=1}^{K} z^k = 1, \quad z^k \geq 0, \quad k = 1, \ldots, K,
$$

where $z^k$ are the intensity variables and $\beta$ a parameter representing the magnitude by which input must be contracted and outputs expanded (Färe and Grosskopf, 2000). The convexity constraint also ensures that efficient firms are only benchmarked against their peers, that is, firms of similar sizes are compared (Coelli et al., 2005). It must be noted that the differences in the envelopment surface is determined by the underlying assumptions of the DEA model. In general the constant returns to scale (CRS) and VRS assumptions are used. The VRS embodies both increasing and decreasing returns to scale. That is to say, the VRS frontier reflects the possibility of production technology exhibiting increasing, constant, and decreasing returns to scale. In this Chapter the VRS is employed with the implicit assumption that the fishery is subject to VRS, with a long-run objective in mind.

In order to establish the dual relationship between the profit function and the DDF the translated vector is proved to be feasible (Färe and Grosskopf, 2000). This means that the translated vectors of the inputs and outputs belong to the

---

8For more details on DEA estimations and returns to scale assumptions, see Coelli, et al. (2005).
technology set. The translated vector is expressed as:

\[
(x - \overrightarrow{D}_T(x, y; -g_x, g_y)g_x, y + \overrightarrow{D}_T(x, y; -g_x, g_y)g_y) \in T
\]

For input and output price vectors, \( w = (w_1, \ldots, w_n) \in \mathbb{R}_{+}^N \), and \( p = (p_1, \ldots, p_m) \in \mathbb{R}_{+}^M \), respectively, the profit function is defined as \( \pi^*(p, w) \geq py - wx \), for all \((x, y) \in T\). This implies that the efficient profit is no less than the value of the feasible input-output vector. Thus, given the feasibility of the translated vector, profit function for the \( k^{th} \) fishing firm can be expressed as:

\[
\pi^*_k(p, w) \geq p \left( y^k + \overrightarrow{D}_T(x^k, y^k; -g_x, g_y)g_y \right) - w \left( x^k - \overrightarrow{D}_T(x^k, y^k; -g_x, g_y)g_x \right), (4.9)
\]

\[
\geq (py^k - wx^k) + \overrightarrow{D}_T(x^k, y^k; -g_x, g_y)(pg_y + wg_x).
\]

This function establishes the relationship between firm \( k^{th} \)'s profit function \( \pi^*_k(p, w) \) and the DDF, \( \overrightarrow{D}_T(x, y; -g_x, g_y) \). This relation can also be interpreted to mean that the firm’s maximal profit is greater than or at least equal to the actual or observed profit, plus the gain in profit resulting from reductions in technical inefficiency. The firm’s maximal profit, given the translated vector, can be re-arranged to establish the duality between the price dual and the quantity primal in a general form as:

\[
\pi^*(p, w) = \text{Max}_{(x, y) \geq 0} \left\{ py - wx + \overrightarrow{D}_T(x, y; -g_x, g_y)(pg_y + wg_x) \right\}. \quad (4.10)
\]

From this the DDF is recovered as:

\[
\overrightarrow{D}_T(x, y; -g_x, g_y) = \text{Max}_{(x, y) \geq 0} \left\{ \frac{\pi^*(p, w) - (py - wx)}{pg_y + wg_x} \right\}. \quad (4.11)
\]
From the firm’s specific profit function established earlier it can be observed, after the necessary re-arrangement, that a firm’s profit efficiency in general can be expressed as:

$$\frac{\pi^*(p, w) - (py - wx)}{pg_y + wg_x} \geq \overrightarrow{D_T}(x, y; -g_x, g_y). \quad (4.12)$$

The above inequality is explained by the possible presence of inefficient allocation of resources even when all technical inefficiencies are eliminated (Fukuyama and Weber, 2004). For example, in Figure 4.4 it is observed that though firm \(F_2\) is technically efficient for being on the efficient frontier, it is not profit efficient. The presence of inefficient resource allocation in firm \(F_2\) is a possible source of its profit inefficiency.\(^9\) The inequality is thus closed when the allocative inefficiency component is added, resulting in equality of the above expression. This means that the allocative inefficiency is residually recovered from the Nerlovian profit and technical (DDF) inefficiencies. It should be observed that the elimination of technical and allocative inefficiencies is expected, all else remaining constant, to achieve full efficiency. The equality between the profit, technical, and allocative efficiencies is given by the following expression:

$$\frac{\pi^*(p, w) - (py - wx)}{pg_y + wg_x} = \overrightarrow{D_T}(x, y; -g_x, g_y) + AE. \quad (4.13)$$

The left hand side, the price dual, of this equation is thus the normalized deviations between the firm’s maximum attainable profit and the observed (actual) profit in the Nerlovian efficiency measure. The right hand side, the quantity primal, is the technical and allocative efficiencies (Färe et al., 1997; Chambers et al., 1998). By technical efficiency it is meant by how much a decision-making unit (DMU) is able

\(^9\)The presence of other possible sources of inefficiency is explored in the next Chapter.
to increase outputs and decrease inputs in order to maximize profit. Allocative efficiency, on the other hand, reflects the additional profit attainable through optimal choices in the input-output mix. In the fisheries under consideration since output is controlled through a firm’s quota, allocative efficiency may primarily result from effort/input choices within a firm’s quota to take advantage of input-output prices in any given fishing season. This gives the full decomposition of the NE into technical (DDF) and allocative efficiency (AE) measures. In practice the directional vectors are set to the value of the observations. This means \( g_x = x \), and \( g_y = y \).

We have set up the methodology with which we estimate profit efficiency. That is, first details of the Nerlovian measure were discussed, then the DDF was introduced and explained. We will use these measures to compute profit efficiency for South Australia rock lobster fishery in Section 4.6, but first we introduce the concept of a meta-frontier as a way in which we analyze the profit efficiency estimates.

### 4.4 Meta-Frontier Analysis

This Section introduces the meta-frontier concept. The Section further shows how the concept is applied to accommodate the possibility that variations in natural endowment and technological differences across firms may lead to biased efficiency estimates when only regional frontiers, other than a ‘global’ frontier, are considered. In Section 4.2, the geological, ecological and environmental differences between the two fisheries, Northern and Southern, were clearly outlined. We apply the meta-frontier concept to these fisheries to investigate differences in efficiency measures, if any, between the two fisheries. We consider the meta-frontier analysis here important because even though technology may be fundamentally the same it is necessary
to consider the ecological and geographical differences in order to make any meaningful comparisons across the two fisheries. In addition, as explained earlier in this Chapter, operational strategies differ across the two fisheries; whereas the Southern fishery operates a day fishing trip, the Northern fishery operates a one to ten days trip.

The meta-frontier concept, proposed by Hayami and Ruttan (1971), was defined as the envelope of commonly conceived classical production function (Mulwa and Emrouznejad, 2011). Meta-frontier was later considered as some form of global frontier, capturing regional (zonal) specific characteristics in an enveloping frontier to make efficiency comparisons across regions more meaningful (Battese et al., 2004). In this sense the efficiency of a production unit is assessed with reference to its own region (zone) frontier, but the production environment facing the region is assessed through the distance between the regional (zonal) frontier and the meta-frontier (O’Donnell et al., 2010). In the efficiency literature the meta-frontier model was introduced to accommodate the possibility that regional variations in natural endowment and technological differences across firms may lead to biased estimates of efficiency scores (Assaf and Matawie, 2010; Zibaei, 2012). It has been demonstrated that the use of traditional production models to compare the efficiency of firms with diverse environmental backgrounds is not appropriate (O’Donnell et al., 2008). Meta-frontier analysis is shown to consider possible variations across firms in efficiency investigations. The application of frontier models in the assessment of efficiency levels in fisheries remains popular, however, meta-frontier models in the fisheries economics literature are not common (Zibaei, 2012).

Efficiency analysis is often based on the assumption that all production units are similar, operating under similar production technology and, therefore, these units can be evaluated under a single frontier (O’Donnell et al., 2010). On the other hand,
evidence shows that production units in a given sample may operate in slightly different production environments giving rise to different production possibility sets. Differences in social, physical, and economic characteristics may be reflected in the heterogeneity of production technologies across firms (O’Donnell et al., 2008). Given such environmental heterogeneity production units may make choices from different production possibility sets. In such situations, estimating efficiency under a single frontier will yield efficiency estimates that do not accurately measure the capacity of the production units (O’Donnell et al., 2010). Comparing efficiency levels of decision-making units (DMUs) across regions with different environmental, ecological and other characteristics, the frontier for the regions must be the same (O’Donnell et al., 2008). The meta-frontier approach allows for evaluation and comparison of the efficiency of production units having access to different production possibility sets (Battese et al., 2004). Currently the meta-frontier approach is common in efficiency analysis in finance and banking (O’Donnell and Westhuizen, 2002; O’Donnell et al., 2008; Kontolaimou and Tsekouras, 2010), education (McMillan and Chan, 2006), agriculture (Hayami and Ruttan (1971); Mulwa et al., 2009), the tourism and hospitality industry (Mulwa and Emrouznejad, 2011), but few in fisheries (Zibaei, 2012).

The Northern and Southern Zone rock lobster fisheries of South Australia possess distinctive differences in their geological, ecological, and environmental characteristics, as earlier outlined. Ignoring the distinct features of these fisheries in any efficiency comparison of the two may lead to biased efficiency scores and therefore result in misleading policy implications (Battese et al., 2004). We use the meta-frontier model to analyze and compare the Nerlovian profit efficiency measures of the Northern and Southern Zone rock lobster fisheries of South Australia.

As mentioned elsewhere in this Chapter parametric and non-parametric methods are usually employed in efficiency investigations, including meta-frontier efficiency
analysis. The non-parametric data envelopment analysis (DEA) method is used in this study. The DEA technique has been discussed earlier. In the Section that follows the meta-frontier is introduced and details of the meta-frontier technology explained.

4.4.1 Meta-frontier framework

This Section outlines the theoretical framework of the meta-frontier method. The set up considers $V > 1$ fishing zones, the Northern and Southern fisheries, with each region having $k = 1, 2, ..., K$ decision-making units, the fishing firms. Specifically, for each $v$—region we assume there exits $v_k$ firms such that $v_k \in V_K$, where $V_K$ is the set of all firms in all zones. Fishing firms in each zone, $v$, are also assumed to operate under region specific technology, $T^v$.

4.4.1.1 The frontiers

The following theoretical formulation largely follows Rao et al. (2003) and Battese et al. (2004). For strictly positive input vectors $x \in \mathbb{R}_+^N$, the set of all inputs which can produce a defined set of positive output vector $y$ (i.e., $y \in \mathbb{R}_+^M$), given a production technology set $T$, can be expressed as: $X(y) = \{x : (x, y) \in T\}$. The boundaries of this set define the ‘isoquants’ (Rao et al., 2003). The set of all output vectors that any input vector, $x$, can produce given the production technology $T$, can also be defined as: $Y(x) = \{y : (x, y) \in T\}$. The boundary of the output set defines the production possibility frontier which represents the technically efficient production. Battese et al. (2004) then describe the meta-frontier as a production
function ‘enveloping’ separate regional (in this case, zonal) production technology sets with each having its own defined environmental factors.

The above formulation means that for positive input and output vectors $x \in \mathbb{R}^N_+$ and $y \in \mathbb{R}^M_+$, respectively, the production possibility set, technology, of each zone $v$, can be defined as:

$$T^v = \{(x, y) : x \in \mathbb{R}^N_+, \text{ can produce } y \in \mathbb{R}^M_+\}.$$

Given $T^v$, the meta-frontier technology set is defined (Battese et al., 2004) as:

$$T^* = \{(x, y) : x \in \mathbb{R}^N_+, \text{ can produce } y \in \mathbb{R}^M_+ \text{ in at least one zonal technology, } T^1, T^2, \ldots, T^V\}.$$

This means that a given input-output combination $(x, y)$, in any given zone, $v$, is part of the meta-frontier technology, $T^*$. In each zone $v$ technology, $T^v$, all the production axioms, including weak disposability, closedness and boundedness, and convexity, are assumed. Rao et al. (2003) show that if the regional (zonal) technologies defining the meta-frontier technology satisfy all the production axioms then $T^*$ also satisfies these axioms except the convexity axiom. To ensure that the meta-frontier technology satisfies the convexity axiom, $T^*$ is defined as the convex monotone hull of the region specific technologies (Rao et al., 2003) and expressed as:

$$T^* \equiv Convex \ monotone\ hull \ \{T^1 \cup T^2 \cup \ldots \cup T^V\}.$$

The meta-frontier is then constructed by pooling all observation units from each region (zone) (Battese et al., 2004). Detailed description of the frontier concept is
given in Section 4.3.2 above. Figure 4.5 below is an illustration of the meta-frontier construction. In Figure 4.5, the meta-frontier envelopes all the three regional frontiers. Like the frontiers earlier discussed in Section 4.3.2, the variable returns to scale (VRS) assumption implies that points lying on the meta-frontier define the envelope and are technically efficient, while points lying below the frontier, in this case the regional frontiers below it, are not efficient. The closeness of each regional frontier to the meta-frontier is defined by the distance of each regional frontier from the meta-frontier. This means in Figure 4.5, the frontier of region 2 is closest to the meta-frontier and therefore firms in this region are, on average, more efficient compared to firms in regions 3 and 1, whose frontiers lie below that of region 2. Region 1 being the farthest from the meta-frontier means that firms in region 1 are, on average, least efficient compared to firms in regions 2 and 3.

Figure 4.5: A graphical illustration of meta-frontier and regional (zonal) frontiers.
4.4.1.2 Profit efficiency under meta-frontier

Profit efficiency can be considered as a measure of the distance between a given profit generated by an input-output combination and an optimal point on a profit frontier. From the meta-frontier technology concept it is feasible to identify regional profit efficiency frontiers, applying DEA to the data on the decision-making units from the zones (regions) (Mulwa and Emrouznejad, 2011). We follow Mulwa and Emrouznejad and use the DEA method discussed earlier in this Chapter to construct $L$ zonal (regional) frontiers, one for each zone (region), $v$, with data on each fishing firm $k$ (i.e., data on $k = 1, 2, ..., K$). The VRS assumption is used here to specify the LP for the frontier, for same reasons earlier discussed.

The LP for the maximum profit of the $k^{th}$ fishing firm, in region $v$ is expressed as:

$$\pi^{vk}(p, w) = \text{Max}_{x, y} \sum_{m=1}^{M} p^{vk}_m y^{vk}_m - \sum_{n=1}^{N} w^{vk}_n x^{vk}_n$$  (4.14)

subject to

$$\sum_{k=1}^{K} z^{vk} y^{vk}_m \geq y^{vk}_m, \quad m = 1, \ldots, M$$

$$\sum_{k=1}^{K} z^{vk} x^{vk}_n \geq x^{vk}_n, \quad n = 1, \ldots, N$$

$$\sum_{k=1}^{K} z^{vk} = 1, \quad z^{vk} \geq 0, \quad k = 1, \ldots, K$$

Notice that the above maximum profit function is a simple transformation of the profit function introduced in Section 3. The vector $y^{vk}_m$ is the $(K \times M)$ output quantities for the $k^{th}$ fishing firm in Zone $v$; $x^{vk}_n$ is the $(K \times N)$ input quantity vector for the $k^{th}$ fishing firm in zone $v$; and $z^{vk}$, the vector of weights. The
maximum profit for the $k^{th}$ firm in zone $v$, given respective output and input price vectors, $p$ and $w$, is denoted as $\pi^{vk}(p, w)$. The LP is solved $K$ times, once for each region, $v$, and producing optimal input-output vectors $(x^{vk}_n, y^{vk}_m)$ which give maximum profit, and $z^{vk}$ vectors.

Construction of the meta-frontier, as explained earlier, is by pooling observations of all decision-making units from all zones (regions). This means the $K$ fishing firms in all the zones will give a number of frontiers from the pooled data. Representing the total number of frontiers generated by $L (l = 1, 2, ..., L)$, the resulting LP model for the $k^{th}$ firm in zone $v$, consisting of the input-output matrices of the pooled data, is expressed (Mulwa and Emrouznejad, 2011) as:

$$\pi^{*lk}(p, w) = \max_{x, y} \sum_{m=1}^{M} p_{lk}^{jm} y_{m}^{*lk} - \sum_{n=1}^{N} w_{lk}^{jn} x_{n}^{*lk}$$

subject to

$$\sum_{k=1}^{K} \sum_{l=1}^{L} z^{lk} y_{m}^{lk} \geq y_{m}^{*lk}, \quad m = 1, \ldots, M$$

$$\sum_{k=1}^{K} \sum_{l=1}^{L} z^{lk} x_{n}^{lk} \geq x_{n}^{*lk}, \quad n = 1, \ldots, N$$

$$\sum_{k=1}^{K} \sum_{l=1}^{L} z^{lk} = 1, \quad z \geq 0, \quad l = 1, \ldots, L$$

and $k = 1, \ldots, K$

$\pi^{*lk}(p, w)$ is maximum profit in the meta-frontier, given price vectors $(p, w)$. The matrix of output quantities of the $k^{th}$ firm in the meta-frontier is given by $y^{lk}_m$. Similarly, in the meta-frontier are: $x^{lk}_n$, the matrix of unit $k$’s input quantities; and
\( z^{lk} \), the vector of weights. The input and output vector values \((x^{*lk}, y^{*lk})\), give the maximum profits obtained from the meta-frontier.

### 4.4.1.3 The Directional distance function under meta-frontier

Like the profit efficiency under meta-frontier discussed above, the technical inefficiency (DDF) for the zonal (regional) frontiers is similarly obtained by simple transformation of the DDF function introduced in Section 3.2, and expressed as:

\[
\overrightarrow{D_T}^{vk}(x^{vk}, y^{vk}; g_x, -g_y).
\]

In addition, running the LP for the transformed version of the DDF produces the technical inefficiency for the \(k^{th}\) firm in region \(v\). A similar transformation of the zonal (regional) technical inefficiency estimates computed by the DEA program for the meta-frontier is expressed as:

\[
\overrightarrow{D_T}^{lk}(x^{lk}, y^{lk}; g_x, -g_y).
\]

(4.16)

It is noted that the maximum profit, \(\pi^{*vk}(p, w)\), of any \(k^{th}\) unit in a given zone, \(v\), is no larger than the meta-frontier profit, \(\pi^{*lk}(p, w)\). This results from the fact that the constraints in the regional LP are a subset of the constraints imposed on the meta-frontier LP problem (Mulwa and Emrouznejad, 2011). Likewise, the zonal frontier of the technical inefficiency estimates, \(\overrightarrow{D_T}^{vk}(x^{vk}, y^{vk}; g_x, -g_y)\), are also no larger than the meta-frontier technical inefficiency estimates, \(\overrightarrow{D_T}^{lk}(x^{lk}, y^{lk}; g_x, -g_y)\).

Analogically, the decomposed Nerlovian profit efficiency estimates for the zonal and
the meta-frontiers are respectively expressed as:

\[
\frac{\pi^*v_k(p, w) - (py^v_k - wx^v_k)}{pg_y + wg_x} = D_T^{v_k}(x^{v_k}, y^{v_k}; g_x, -g_y) + \rightarrow AE_T^{v_k} 
\]

and

\[
\frac{\pi^*l_k(p, w) - (py^l_k - wx^l_k)}{pg_y + wg_x} = D_T^{l_k}(x^{l_k}, y^{l_k}; g_x, -g_y) + \rightarrow AE_T^{l_k},
\]

where; \(\rightarrow AE_T^{v_k}\) and \(\rightarrow AE_T^{l_k}\), are the zonal and meta-frontiers of the allocative inefficiencies, respectively.

Now that we have definition of profit efficiency and its decomposition into technical and allocative components and the ability to compare across regions using meta-frontier, we can turn to the particular fishery question. To do this we first give detailed description of the data used in the next Section.

### 4.5 Data Description

Data on the South Australian Northern and Southern Zone rock lobster fisheries were obtained from EconSearch. EconSearch collects confidential survey data from fishing operators in the Northern and Southern Zone fisheries for the estimation of various economic indicators. According to EconSearch, though fishers in the rock lobster fishery may hold other licenses, data collected on rock lobster are strictly in relation to rock lobster licenses only. This means costs and profits can be solely attributed to rock lobster fishing activities. The data are cross-sectional, covering the fishing periods 1997/98, 2000/01, 2004/05, and 2007/08. The surveys
are voluntary, and due to legal reasons no identifiers are used. It is therefore not possible to track individual vessels over time. For each of these time periods the data are grouped separately into Northern (NZ) and Southern (SZ) zones. The data are grouped into four categories: boat variable costs, other variable costs, quasi-fixed, and fixed costs. Boat variable costs include: fuel, oil and grease, bait, ice, provisions, crew payments, fishing equipment (nets, pots, lines, etc), repairs and maintenance (sliping, painting, overhaul motor). Other variable costs include owner-operated and unpaid family labour.

The data had a few challenges which included missing (incomplete) observations, as well as some outliers. There were a number of firms with either zero or missing output and, or input values. This required that the data be cleaned. Our data cleaning process included the following. For observations with missing or incomplete values we first look for firms with similar input (or output values if it is missing input values) values (i.e., for each zone); we then compute the mean values and standard deviations, and then make estimates for the missing values. Outliers were first detected from scatter plots, then using similar approach as in the case of missing observations, we make estimates for such observations.

The family labour cost is imputed based on amount of time and equivalent wage rates. Fixed and quasi-fixed costs, measured in current dollar values, include insurance, license and industry fees, office and business administrative costs, interest on loan repayment and overdraft, depreciation and leasing. The data also include boat catches, individual boat quotas, average beach price, as well as unit input costs. Tables 4.1 and 4.2, respectively, provide summary statistics of the discretionary variable and fixed inputs of the Northern and the Southern Zone fisheries, before grouping into the four categories mentioned above. The Tables show cost distributions across firms in both fisheries, with both fixed and variable costs, on average, being higher in the Northern Zone than in the Southern Zone.
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<td>45445</td>
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<td>15502</td>
<td>18161</td>
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<td>Repairs &amp; Maintenance</td>
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<td>18415</td>
<td>12299</td>
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<td>16750</td>
<td>13963</td>
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<td>7954</td>
<td>8906</td>
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<td>4566</td>
<td>4609</td>
<td>11421</td>
<td>3617</td>
<td>285</td>
<td>299</td>
<td>695</td>
</tr>
<tr>
<td>Labour paid</td>
<td>93550</td>
<td>128122</td>
<td>63406</td>
<td>70301</td>
<td>79973</td>
<td>83531</td>
<td>59044</td>
<td>107488</td>
</tr>
<tr>
<td>Labour unpaid</td>
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<td>17905</td>
<td>19077</td>
<td>21557</td>
<td>23433</td>
<td>17822</td>
<td>20862</td>
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<td>3309</td>
<td>5051</td>
<td>976</td>
<td>2408</td>
<td>4472</td>
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<td>693</td>
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<tr>
<td>Total variable cost</td>
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<td>247108</td>
<td>171805</td>
<td>184477</td>
<td>152814</td>
<td>14164</td>
<td>124583</td>
<td>216047</td>
</tr>
</tbody>
</table>

No. of Observations: 18 24 22 19

NB: Figures in each column are the means, standard deviations, minimum and maximum values, respectively.
All Figures are in Australian Dollars.
Data source: EconSearch.

<table>
<thead>
<tr>
<th>Quasi-fixed/fixed inputs</th>
<th>Northern Zone</th>
<th>Southern Zone</th>
<th>Statistics</th>
<th>Statistics</th>
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<td>19382</td>
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<tr>
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<td>(1455)</td>
<td>(5748)</td>
<td>(5427)</td>
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<td>[9091, 15455]</td>
<td>[15000, 37800]</td>
<td>[12000, 35000]</td>
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<td>14939</td>
<td>8439</td>
<td>7427</td>
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<tr>
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<td>(2733)</td>
<td>(2923)</td>
<td>(3144)</td>
<td>(2677)</td>
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<tr>
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<td>[4545, 8717]</td>
<td>[2872, 16000]</td>
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<td>35464</td>
<td>31500</td>
<td>42709</td>
</tr>
<tr>
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<td>(23029)</td>
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<td>(41287)</td>
<td>(49973)</td>
</tr>
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<td>[0.00, 163020]</td>
<td>[0.00, 150000]</td>
<td>[0.00, 182250]</td>
</tr>
<tr>
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<td>13065</td>
<td>8486</td>
</tr>
<tr>
<td></td>
<td>(5971)</td>
<td>(6278)</td>
<td>(123101)</td>
<td>(5425)</td>
</tr>
<tr>
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<td>[0.00, 23021]</td>
<td>[0.00, 45362]</td>
<td>[0.00, 17062]</td>
</tr>
<tr>
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<td>79483</td>
<td>76739</td>
</tr>
<tr>
<td></td>
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<td>(30769)</td>
<td>(46988)</td>
<td>(36657)</td>
</tr>
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<td>[33637, 164814]</td>
<td>[23074, 240333]</td>
<td>[21475, 170533]</td>
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<td>151868</td>
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<tr>
<td></td>
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<td>(45385)</td>
<td>(62748)</td>
<td>(52445)</td>
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<tr>
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<td>[63091, 244640]</td>
<td>[51130, 307873]</td>
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<td>[15610, 104023]</td>
<td>[14756, 140291]</td>
<td>[18304, 160840]</td>
<td>[17391, 157566]</td>
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<td>26</td>
<td>22</td>
<td>19</td>
</tr>
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<td>26</td>
<td>26</td>
<td>82</td>
<td>55</td>
</tr>
</tbody>
</table>

NB: Figures in each column are the means, standard deviations, minimum and maximum values, respectively.
All Figures are in Australian Dollars.

Data source: EconSearch.
In standard DEA applications when inputs are treated as choice variables the implicit assumption is that firms can vary all inputs to achieve efficiency. This corresponds to a long run analysis (Das and Ghosh, 2009). For analytical purposes we make this implicit assumption and treat all inputs as variable. We select the inputs believed to adequately describe the operations of the fisheries, and clean out outliers from the data. These data are used in the computation of the profit, directional distance, and allocative efficiency scores. Only the selected discretionary inputs are used. Discretionary inputs are those inputs whose quantities can be varied by the fisher at will, and do not necessarily take into account environmental or non-discretionary inputs (Alfonso and Aubyn, 2008). However, differences such as boat engine capacity, engine age, boat size or length, as well as zone specific characteristics may all contribute to heterogeneity among various firms even within the same fishery (that is, the South Australian rock lobster fishery), and therefore influence firms’ profit efficiency.\textsuperscript{10}

We investigate two versions of the frontier analysis; the zone (region) specific frontier, and the meta-frontier. In the zone specific frontier we analyze firm performance in each zone separately. We do this on the assumption that firms within each separate zone are homogeneous. In order to compare firm performance across zones we carry out the meta-frontier analysis. The underlying assumption in the meta-frontier case is that zone characteristics are different across different zones, making firms heterogeneous when grouped together, that is, when grouped as one fishery.

The data also capture estimated biomass levels, boat length, boat age, engine age, and electronic equipment age. Average values of these non-discretionary variables are provided in Table B.2 in Appendix A. The 1997/98 period average values for the Northern Zone are generally lower compared to those of its Southern counterpart.\textsuperscript{10}

\textsuperscript{10}This is investigated in the next Chapter.
A similar picture is observed for the 2000/01 period, except for electronic equipment age where the Northern Zone average is higher. The 2004/05 averages, on the other hand, show Northern Zone with much higher averages for boat age and electronic age. Northern Zone averages are, however, only higher in boat age and lower in all others, for the 2007/08 period. These variables are assumed to be accounting for regional differences and, therefore, used as non-discretionary variables in the truncation regression analysis that follow this Chapter.

In the Section that follows we give full description of the data organization for the computation of the zonal and meta-frontier efficiency measures. The Section first describes the data organization, then the computational process of the Nerlovian profit efficiency, the technical and allocative efficiencies for both the zonal and meta-frontiers. We then analyze the results of the zonal efficiency measures, compare the meta-frontier measures, and discuss the results.

### 4.6 Empirical Application and Analysis

Non-parametric profit efficiency evaluation starts with the computation of maximum attainable profit using DEA. We compute the maximum attainable profit of each firm and subtract from it the corresponding observed profits. Using the procedure described in Section 3, this yields the Nerlovian profit efficiency score (NE) for each firm. This is done for firms in both the Northern and Southern Zone fisheries for each fishing period, separately. Following the description of the DDF procedure in Section 4.3, we compute the DDF for each firm in each fishery separately, for each fishing period. The difference between the NE and the DDF scores then gives the AE scores as earlier described. The NE, as well as the DDF and, therefore, the AE, are bounded between 0 and 1. It must be emphasized that
the Nerlovian and the technical measures are inefficiency measures, and so also are
the allocative measures. This means that the closer the score is to 0 the lesser the
level of inefficiency (or the higher the efficiency). In other words, a firm is more
efficient the closer its measure is to 0, and less efficient the closer the measure is
to 1. Following the theoretical framework in Section 4.4, we also pool the data for
the two zones for each period and compute the meta-frontiers for the four periods.
This is done using similar procedures described for the estimation of the individual
zone efficiency estimates mentioned above. In the next Section these procedures
are detailed.

4.6.1 Application

To compute the Nerlovian efficiency scores we organize the data in the following way.
We first identify firm level input and output vectors. Output in this case is firms’ fish
catch or harvest, measured in tonnes. Firm level input and output price vectors are
also specified. Inputs were grouped into four categories as earlier mentioned; boat
variable inputs, other variable inputs, quasi-fixed, and fixed inputs. Categorising
inputs into four groups was aimed at reducing the number of variables as much as
possible. This is important in DEA applications, particularly for small sample sizes
as in our case, in order to avoid the curse of dimensionality. We include quasi-fixed
and fixed inputs in order to measure efficiency at full equity. We use profit at
full equity with the objective of analyzing the firms’ efficiency in medium and long
term horizon. Besides, profit at full equity is also considered a more useful absolute
measure of economic performance of fishing firms (EconSearch, 2011). These inputs
were aggregated using common denominators considered appropriate for each input
type. For example, for inputs that are denominated by days fished, number of days
fished is used as a common denominator for the aggregation. In other words,
variables considered directly related to either days at sea, or harvest, were grouped accordingly. Objectives of the aggregation are two fold. First, to reduce the number of variables used in the DEA function. This was to help minimize the dimensionality problem as much as possible, given the small number of observations, particularly in the case of the Northern Zone. The second objective was to help gauge out input prices. Input price were not available and since the costs were dollar denominated, one way of obtaining unit prices was using the denominators as explained. For each fishery/zone we obtain input and output price vectors. These are one output vector, and a corresponding price vector, and four input vectors, together with their corresponding price vectors.

The Nerlovian efficiency measure is computed by first estimating the maximum profits. We do this using the maximum profit DEA function specified in Equation (4.6), Section 4.3.1. In this Chapter we use the profit.max program in Frontier Efficiency Analysis package with R, also known as FEAR.\textsuperscript{11} Loading the organized data into this program we obtain the optimal outputs and inputs for the frontier for each Zone, that is, in the case of the Zone specific frontiers. In the case of the meta-frontier the optimal output and input are obtained for the meta-frontier, based on Equation (4.15). These optimal outputs and inputs, given prices, are then used to compute the optimal profit for each firm. The sensitivity of the DEA program requires that outliers are cleaned out of the data. The optimal profits are the maximum profits firms could achieve given the same input outlays. The fisheries in each zone can achieve these maximum profits if they are able to increase output levels to the optimal levels, compared to their actual observed output levels.

To estimate the Nerlovian measure in Equation (4.1), the denominator of this equation must be specified using the directional vector, \( g = (g_y - g_x) \). The literature

\textsuperscript{11} For details on this program, see Wilson (2010)
indicates that if firms’ technology is such that the maximum profit function produces same optimal inputs and outputs for all the firms in the group, then the direction to choose is \( g = (y^*, x^*) \), where \( y^*, x^* \) are, respectively, optimal outputs and inputs. In cases where the optimal inputs and outputs vary across firms or are not the same for each firm, the direction to choose could be \( g = (1, -1) \) or \( g = (\bar{y}, \bar{x}) \). In this case \( \bar{y}, \bar{x} \), are mean output-input vectors (Fukuyama and Weber, 2004). In this Chapter the direction \( g = (y^*, x^*) \) is chosen in periods where the optimal inputs and outputs are not the same across firms and \( g = (\bar{y}, \bar{x}) \), where otherwise. This means that the denominator for the Nerlovian equation, Equation (4.1), is either \( (py^* + px^*) \) or \( (p\bar{y} + w\bar{x}) \). For either option the price vectors, \( (p, w) \), are multiplied by their corresponding outputs and inputs and summed. The Nerlovian measure for the meta-frontier is estimated by first using the profit.max program to estimate Equation (4.15).

It was earlier mentioned that some methods, for example the index methods, computationally do not allow negative profit firms to be examined in profitability analysis. Such firms are excluded from observations before any computation is done. The Nerlovian method, on the other hand, computationally makes it possible for such firms to be included in the observations and examined. However, we observe in this Chapter, that firms making excess losses end up with a Nerlovian measure greater than 1, because the numerator exceeds the denominator in Equation (4.1), in such cases. Given that a measure of 1 indicates complete inefficiency (i.e., 100% inefficient) any measure exceeding 1 does not yield any meaningful economic interpretation. For this reason such firms are excluded from further analysis. We drop about 7% of the observations (i.e., 6 observations out of 89 from the Northern Zone and nearly 5% (i.e., 9 out of 189) from the Southern Zone. We note that these numbers are not significantly large enough to affect our results in any significant way. For example, as it can be observed from Figure 4, truncating these observa-
tions at 1 and including them in the analysis do not change the skewness of the distribution. We, therefore, do not consider the exclusion of these observations as problematic as far as the numbers and our results are concerned. On the other hand, we note that in fisheries and in other resource industries, where negative profit is not rare the NE may not be solving the negative profit problem entirely. Nevertheless, it is important to consider the ability to include all firms in the initial stage and be able to compute their profit efficiency as a good thing. This is an advantage of the Nerlovian method. The ability to compute the profit efficiency of each firm, whether or not the firm is making negative profits, offers some necessary information about individual firm performance. It offers managers of such firms the opportunity to appreciate the seriousness of the challenges they face and adopt necessary strategies to address them.

The technical (DDF) efficiency measure is estimated using the ddf program contained in the nonparaeff package in FEAR. For the estimation of this measure, the DDF specified in Equation (4.8), a directional vector must be chosen. The choice of the vector is informed by the optimal outputs and inputs resulting from the maximum profit function. For varying optimal output and inputs, either of two directions, \( g = (1, -1) \) and \( g = (\bar{y}, \bar{x}) \) are used. The direction \( g = (y^*, x^*) \) is recommended if optimal outputs and inputs are the same for all firms. Details were earlier discussed under the Nerlovian measure. The allocative inefficiency is then residually determined from Equation (4.4). The meta-frontier version of the DDF, Equation (4.16), is estimated using the ddf program. The meta-frontier allocative inefficiency is then established using the decomposition provided by Equation (4.18).

The DEA applications used in this Chapter, particularly the directional distance function, have been known to be sensitive to small sample sizes and number of
variables used, known in the literature as the dimensionality problem. Given the sample sizes used in this Chapter it is important to employ statistical measures that will help draw accurate statistical inference. To do this we use the non-parametric bootstrap technique to bootstrap the efficiency estimates. The bootstrapping is done at this stage for a number of reasons. The bootstrap technique is useful in empirical applications when the theoretical distributions of the population is unknown. Using this non-parametric technique does not require any assumptions about the distribution of the population. It is also useful for making meaningful statistical inference when dealing with small sample sizes. Our sample sizes are small in many cases, particularly the Northern Zone (mostly less than 30 observations), so by re-sampling the estimates with re-placement we are able to draw reasonable statistical inference about the estimates in the population. Using the bootstrap we draw different random samples from the observations in each zone by re-sampling with replacement. We use 5000 replications in each case. The method produces a distribution of the efficiency means, together with statistical properties such as standard errors, estimated biases, and bias corrected accelerated intervals (BCas) that make it possible to make the necessary statistical inferences. From the BCas the limits within which the unknown population efficiency means lie are identified, with some degree of confidence. We choose 95% confidence level in this case. The BCa is used to ensure extra accuracy. In Section 4.6.2 the results of the estimations are provided and analyzed.

4.6.2 Results and analysis

The inefficiency estimates are provided here in three parts: the zonal periods (i.e., zonal frontiers for each period); the period-by-period meta-frontier (i.e., the
meta-frontier estimates for separate periods); and zonal periods and period meta-frontiers.

Table 4.3: Efficiency Estimates (Periods and Period-by-Period Meta-frontiers) : Northern Zone

<table>
<thead>
<tr>
<th>Period</th>
<th>Statistics</th>
<th>Zonal Frontier Estimates (Periods)</th>
<th>Meta-frontier Estimates (Overall)</th>
<th>(Period-by-Period)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Nerlovian</td>
<td>Technical</td>
<td>Allocative</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Profit In eff.</td>
<td>In eff.</td>
<td>In eff.</td>
</tr>
<tr>
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<td>Mean</td>
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<td>0.0606</td>
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</tr>
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<td>0.0002</td>
<td>-0.0003</td>
</tr>
<tr>
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<td>BCA</td>
<td>(0.1140, 0.2613)</td>
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<td>(0.0965, 0.1906)</td>
</tr>
<tr>
<td>Northern</td>
<td>Mean</td>
<td>0.2355</td>
<td>0.0582</td>
<td>0.1773</td>
</tr>
<tr>
<td>2000/01</td>
<td>Min/Max</td>
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<td>[0.0, 0.2289]</td>
<td>[0.0, 0.3308]</td>
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<td>0.0000</td>
<td>-0.0000</td>
</tr>
<tr>
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<td>(0.0939, 0.2444)</td>
<td>(0.1393, 0.2144)</td>
</tr>
<tr>
<td>Northern</td>
<td>Mean</td>
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<td>0.2023</td>
<td>0.1625</td>
</tr>
<tr>
<td>2004/05</td>
<td>Min/Max</td>
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<td>[0.0, 0.4728]</td>
<td>[0.0, 0.54670]</td>
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<td>0.0000</td>
<td>0.0003</td>
</tr>
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<td>(0.1921, 0.2662)</td>
<td>(0.1042, 0.2435)</td>
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<td>Mean</td>
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<td>0.0591</td>
<td>0.2280</td>
</tr>
<tr>
<td>2007/08</td>
<td>Min/Max</td>
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<td>[0.0, 0.5277]</td>
<td>[0.0, 0.5072]</td>
</tr>
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<td>-0.0001</td>
<td>0.0002</td>
</tr>
<tr>
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<td>(0.2240, 0.3691)</td>
<td>(0.0214, 0.1616)</td>
<td>(0.1783, 0.2836)</td>
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</table>

NB: The values are inefficiency measures. For example, 0.2005 means 20.05% inefficiency (i.e., 80% efficiency). Notice that in the overall meta-frontier estimates column we report the same results for the Northern Zone. This is so because as illustrated in Figure 4.5, these represent the same meta-frontier against which the two zones are evaluated.

In each part mean, minimum, and maximum estimates, estimated bias, and bias corrected accelerated intervals are provided. First, we analyze the zonal period frontier inefficiency estimates and then compare with the corresponding overall period meta-frontier estimates. We then do a comparative analysis of the zones for each period, by comparing their period-by-period meta-frontier estimates. We also provide evidence to show that the meta-frontier mean estimates for the two zones are statistically different. To do this we hypothesize that the distributions of mean inefficiency measures in the two zones are equal, and use the Welch two sample
t-test to test the hypothesis. We find this necessary because in absolute terms the means of the meta-frontier estimates for the two zones appear to be close. Tables 4.3 and 4.4 show results for the Northern and Southern Zones, together with the corresponding overall meta-frontier estimates.

Table 4.4: Efficiency Estimates (Periods and Period-by-Period Meta-frontiers) : Southern Zones

<table>
<thead>
<tr>
<th>Zone</th>
<th>Statistics</th>
<th>Zonal Frontier Estimates (Periods)</th>
<th>Meta-frontier Estimates (Overall)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Nerlovian Profit</td>
<td>In eff.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>In eff.</td>
<td>In eff.</td>
</tr>
<tr>
<td>Southern</td>
<td>Mean</td>
<td>0.1979</td>
<td>0.0447</td>
</tr>
<tr>
<td>1997/98</td>
<td>Min/Max</td>
<td>[0.0, 0.2590]</td>
<td>[0.0, 0.3109]</td>
</tr>
<tr>
<td></td>
<td>Est. Bias</td>
<td>0.0000</td>
<td>0.0002</td>
</tr>
<tr>
<td></td>
<td>BCa</td>
<td>(0.1062, 0.2592)</td>
<td>(0.1062, 0.2592)</td>
</tr>
<tr>
<td>Southern</td>
<td>Mean</td>
<td>0.2600</td>
<td>0.0731</td>
</tr>
<tr>
<td>2000/01</td>
<td>Min/Max</td>
<td>[0.0, 0.4350]</td>
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<td>Est. Bias</td>
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<td>-0.0000</td>
</tr>
<tr>
<td></td>
<td>BCa</td>
<td>(0.1498, 0.2268)</td>
<td>(0.1498, 0.2268)</td>
</tr>
<tr>
<td>Southern</td>
<td>Mean</td>
<td>0.3357</td>
<td>0.1585</td>
</tr>
<tr>
<td>2004/05</td>
<td>Min/Max</td>
<td>[0.0, 0.5106]</td>
<td>[0.0, 0.3915]</td>
</tr>
<tr>
<td></td>
<td>Est. Bias</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td></td>
<td>BCa</td>
<td>(0.1562, 0.2653)</td>
<td>(0.1562, 0.2653)</td>
</tr>
<tr>
<td>Southern</td>
<td>Mean</td>
<td>0.3016</td>
<td>0.1149</td>
</tr>
<tr>
<td>2007/08</td>
<td>Min/Max</td>
<td>[0.0, 0.5849]</td>
<td>[0.0, 0.5494]</td>
</tr>
<tr>
<td></td>
<td>Est. Bias</td>
<td>-0.0000</td>
<td>-0.0000</td>
</tr>
<tr>
<td></td>
<td>BCa</td>
<td>(0.1562, 0.2244)</td>
<td>(0.1562, 0.2244)</td>
</tr>
</tbody>
</table>

NB: The values are inefficiency measures. For example, 0.2005 means 20.05% inefficiency (i.e., 80% efficiency). Notice that in the overall meta-frontier estimates column we report the same results for both the Northern and Southern Zones. This is so because as illustrated in Figure 4.5, these represent the same meta-frontier against which the two zones are evaluated.

Let us first consider profit efficiency estimates calculated using only the observations from a single zone and period (left-hand columns of Tables 4.3 and 4.4). These compare inefficiencies only related to the closest peers in time and space. Note that the Nerlovian profit efficiency is broken down into technical and allocative inefficiency components in the subsequent columns.
First, we analyze the period zonal frontier estimates of the Northern Zone (first three columns of the upper part of Table 4.3). In this zone the mean profit inefficiency (efficiency) is lowest (highest), at about 20% (80%), in the 1997/98 fishing period, increasing (decreasing) to the lowest of nearly 36% (64%) in the 2004/05 period. Thereafter, mean profit inefficiency (efficiency) fell (rose) to about 28% (72%) in the 2007/08 fishing period. A close look at the bias accelerated corrected intervals (BCas) shows that the 2007/08 mean is quite close to that of 1997/98. The period mean measures show that profit inefficiency (efficiency) in the Northern Zone can be largely attributed to allocative inefficiency (efficiency), with the exception of the 2004/05 period where technical inefficiency (efficiency) is highest (lowest) at 20% (80%). In all other periods technical inefficiency (efficiency) registers a mean value of 6% (94%), on average. The estimated bias, in all cases, shows that the mean estimates are not significantly corrected upwards or downwards. The relatively higher maximum values in 2004/05 and 2007/08 periods, show that there are greater variations in the distribution of inefficiency measures in these periods compared to other periods.

Next, the Southern Zone period estimates are considered (first three columns of the lower part of Table 4.4). In the Southern Zone the mean profit inefficiency rose from about 20% in 1997/98 fishing period to nearly 34% in the 2004/05 period, falling slightly to approximately 30% in 2007/08. Technical inefficiency also rose from 4% in 1997/98 to the highest of about 16% in 2004/05, falling to nearly 11% in 2007/08. In all cases the allocative inefficiency, which rose from 15% in 1997/98 to about 19% in 2007/08, with just about 1 percentage point drop in 2004/05, explains the profit inefficiencies. It is interesting to note that though the mean profit inefficiency (efficiency) in the 2004/05 period is highest (lowest), the variability in the estimates is not as high as observed in the 1997/98 and 2007/08 periods where inefficiencies (efficiencies) are relatively lower (higher).
In the next two paragraphs we compare the period zonal estimates with corresponding overall period meta-frontier estimates. In the right-hand three columns of Tables 4.3 and 4.4 are the estimates of overall period meta-frontier estimates computed by pooling firms from both zones for each period. That is, using all Northern and Southern Zone observations in each period as peers. Graphically, this would be the meta-frontier picture illustrated in Figure 4.5. We start by looking at the Northern Zone period estimates. The period inefficiency estimates for the Northern Zone are lower than the corresponding period overall meta-frontier estimates. This is expected because firms compared to a small local group of peers may appear to be doing well, but may perform badly when compared with peers from other regions (zones, in this case). The profit inefficiency (efficiency) in the periods appear to be close to the corresponding overall meta-frontier estimates, in absolute terms.

The technical inefficiencies, on the other hand, show significant absolute differences. This is also expected for two reasons. The first is attributed to the fact mentioned earlier; firms in their own group may perform better than when grouped with peers from other groups, that is, when compared with peers in the meta-frontier group. Secondly, the higher number of observations used in the computation of the meta-frontier measures play significant role in correcting for the dimensionality problem and, therefore, reducing biases reflected by small numbers. For example, in the case of the 1997/98 period, the period measures for the zone are obtained using 18 observations, whereas the meta-frontier used 44 observations, that is, 18 from the Northern Zone and 26 from the Southern Zone. Observe that the relatively low technical inefficiency estimates under period zonal frontiers in this case means that profit inefficiency would be largely explained by allocative inefficiencies. Under meta-frontier, however, the picture is not straight forward. Profit inefficiencies in the Northern Zone for 1997/98, under meta-frontier, appear to be equally explained
by technical and allocative inefficiencies, whereas in the 2000/01 and 2007/08 periods profit inefficiencies under meta-frontier are clearly explained by allocative inefficiencies. Profit inefficiency in 2004/05, on the other hand, can be clearly attributed to technical inefficiency. This means that increases in observations under meta-frontier makes it difficult to identify a single source of profit inefficiency for all periods in the zone.

Next, we consider the Southern Zone. In the Southern Zone, as observed in the case of the Northern Zone, the period inefficiency measures are lower than the corresponding meta-frontier measures. Again, unlike the profit inefficiency measures, the technical inefficiencies are much lower for the zonal period estimates than the corresponding meta-frontier estimates. These are expected, and explained by similar reasons given in the Northern case. It is noted, however, that whereas period profit inefficiencies in this zone are clearly explained by allocative inefficiencies for all periods, the meta-frontier profit inefficiency are not the same for different periods. Consequences of the influence of large numbers on technical inefficiency measures and the effect on profit inefficiency under the meta-frontier are discussed in the previous paragraph. It is also observed that the Southern Zone generally accounts for the variations in the profit inefficiency distributions of the meta-frontier, particularly as observed in the minimum and maximum values in the 1997/98 period.

We now explain the possible causes of the inefficiency measures observed in both fisheries. Changes in efficiency levels observed in Tables 4.3 and 4.4, particularly with regards to increase in allocative inefficiency in the Northern Zone, could be attributed to a number of issues identified in the SARDI (2009) report. Between 1998 and 2008 harvest in the Northern Zone declined by nearly 60% with less than proportionate reduction in effort for the same period. Over this period catch per unit of effort (CUE) fell by about 52%, that is, from 1.40kg/pot lift to 0.67kg/pot lift.
Such declines are observed across the MFAs in the zone (SARDI, 2010). Persistent downward movement in CUE is reported over the period 1999 to 2008 (SARDI, 2009). CUE (catch rate) in the zone increased from 1.40kg/pot lift in 1997 to the highest of nearly 1.44kg/pot lift in 1999, falling thereafter to a low of about 0.67kg/pot lift in 2008. The disproportionate declines in effort compared to falls in catch leading to persistent and sharp declines in CUE help explain cost increases, falls (increases) in profit and allocative efficiencies (inefficiencies) over the period under investigation. Fluctuations in biomass, and harvest values in the rock lobster fishery, shown in Figure 4.1, together with falls in boat equity profits (see Figure 4.3) in the period under review further confirm our results.

As in the case of the Northern Zone, our results compare reasonably well with the underlying fundamental changes in in the Southern Zone over the period under investigation. Whereas catch rates declined over the period, effort increased at the same time. The Southern Zone fishery performed best in 2002 in terms of catch rate. After a period of increases in catch rate, from about 0.98kg/pot lift in 1998 to a high of about 2.07kg/pot lift in 2002, the catch rate fell persistently. The fall in CUE reached a low of 1.6kg/pot lift in 2004 (PIRSA, 2007). This trend is observed across all regions (MFAs) in the zone. Effort, on the other hand, increased in the Southern Zone by about 96% between 2003 and 2008 (SARDI, 2009). Other factors such as declines in biomass levels, harvest value, and equity profit levels over the period, as mentioned earlier, help explain the declines in efficiency levels in this zone. Next, we provide comparative analysis of the two fisheries, using their period meta-frontier inefficiency estimates.

In Table 4.5 we compare the inefficiency scores of the Northern and Southern Zones under meta-frontier. From Table 4.5 it is observed that on average the Northern Zone fishery appears to perform a little better than its Southern Zone counterpart,
in absolute terms, across all periods except in 2000/01 fishing period. In general the results appear quite close in absolute terms. To test for equality of mean estimates between the two zones, we use the Welch two sample t-test (i.e., we test if the mean estimates between the zones are equal).

Table 4.5: Inefficiency Estimates (Periods and Period Meta-frontiers): Northern and Southern Zones

<table>
<thead>
<tr>
<th>Period</th>
<th>Statistical Measure</th>
<th>Northern Zone (Period Meta-frontier)</th>
<th>Southern Zone (Period Meta-frontier)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nerlovian Profit Eff.</td>
<td>0.2172</td>
<td>0.2255</td>
</tr>
<tr>
<td></td>
<td>Allocative Eff.</td>
<td>0.1067</td>
<td>0.1078</td>
</tr>
<tr>
<td></td>
<td>Nerlovian Profit Eff.</td>
<td>0.1067</td>
<td>0.1177</td>
</tr>
<tr>
<td></td>
<td>Allocative Eff.</td>
<td>0.1085</td>
<td>0.1185</td>
</tr>
<tr>
<td>1997-98</td>
<td>Min/Max</td>
<td>[0.0151, 0.4529]</td>
<td>[0.0231, 0.8967]</td>
</tr>
<tr>
<td></td>
<td>Est. Bias</td>
<td>0.0000</td>
<td>-0.0000</td>
</tr>
<tr>
<td></td>
<td>BCa</td>
<td>(0.1544, 0.3822)</td>
<td>(0.1692, 0.3331)</td>
</tr>
<tr>
<td></td>
<td>No. of Obs.</td>
<td>18</td>
<td>26</td>
</tr>
<tr>
<td>2000-01</td>
<td>Min/Max</td>
<td>[0.0329, 0.4504]</td>
<td>[0.0035, 0.3750]</td>
</tr>
<tr>
<td></td>
<td>Est. Bias</td>
<td>-0.0002</td>
<td>0.0007</td>
</tr>
<tr>
<td></td>
<td>BCa</td>
<td>(0.2266, 0.3218)</td>
<td>(0.2277, 0.3904)</td>
</tr>
<tr>
<td></td>
<td>No. of Obs.</td>
<td>24</td>
<td>26</td>
</tr>
<tr>
<td>2004-05</td>
<td>Min/Max</td>
<td>[0.0, 0.6387]</td>
<td>[0.09, 0.7092]</td>
</tr>
<tr>
<td></td>
<td>Est. Bias</td>
<td>-0.0008</td>
<td>-0.0000</td>
</tr>
<tr>
<td></td>
<td>BCa</td>
<td>(0.3282, 0.4724)</td>
<td>(0.4375, 0.5039)</td>
</tr>
<tr>
<td></td>
<td>No. of Obs.</td>
<td>22</td>
<td>82</td>
</tr>
<tr>
<td>2007-08</td>
<td>Min/Max</td>
<td>[0.0099, 0.7330]</td>
<td>[0.0, 0.7505]</td>
</tr>
<tr>
<td></td>
<td>Est. Bias</td>
<td>-0.0006</td>
<td>0.0004</td>
</tr>
<tr>
<td></td>
<td>BCa</td>
<td>(0.2418, 0.3810)</td>
<td>(0.2996, 0.3966)</td>
</tr>
<tr>
<td></td>
<td>No. of Obs.</td>
<td>19</td>
<td>55</td>
</tr>
</tbody>
</table>

NB: The values are inefficiency measures. For example, 0.2005 means 20.05% inefficiency (i.e., 80% efficiency)

We do not find enough evidence to reject the alternate hypothesis that the meta-frontier mean inefficiency estimates in the two zones are indeed different. Table B.1 in Appendix B shows results of the t-tests. We note, however, that mean technical inefficiency (efficiency) over the period, 1997 – 2008, on average, are the same at 15% (85%).

To get a more general picture of the distribution of the inefficiency estimates in the two fisheries, Figure 4.6 presents kernel density distribution of the period-by-period
meta-frontier (overall) estimates. To avoid imposing any restrictions on the estimates we use a non-parametric kernel density method, the Epanechnikov method, with different bandwidths for each distribution of the bootstrapped efficiency estimates.\footnote{In practice the Epanechnikov and Gaussian methods are often used. The literature points out that the choice of either of these has little impact on the results. The bandwidths are different for the different efficiency measures since their distributions are different.} We also note that ideally the density graphs should have the same scale for the horizontal axis. However, doing this overly minimizes some of the graphs whose distributions are in smaller intervals. Recall that the efficiency scores for NE, DDF and AE, fall in different intervals. Minimizing some of the graphs would not create the pictorial impression they are meant to have. It is therefore important that the kernel density distributions between zones are viewed within periods and not across periods, to avoid any confusion. Note that the efficiency estimates were replicated using non-parametric bootstrap method with 5000 replications for each. By avoiding imposing restrictions on the estimates we allow the estimates to speak for themselves.
Figure 4.6: Density distributions of bias-corrected meta-frontier (overall) estimates for Nerlovian Ineff., DDF Ineff., and Allocative Ineff. (columns) by period (rows) for Northern Zone (solid blue lines) and Southern Zone (dashed red lines)

These density plots show the percentage of times that a particular inefficiency score is computed. For example, the top left diagram shows that an inefficiency score of approximately 0.22 (22%) was computed nearly 2.5% of the time for the Southern Zone fishery. It can be observed that apart from the 2000/01 and 2004/05 periods...
profit inefficiency estimates are positively skewed to the right. This shows a pull of the mean estimates (the straight lines) more to the right of their modes. In addition, skewness in the Southern Zone distributions is more pronounced than in the Northern Zone. The greater skewness in the Southern fishery offers another possible explanation to its relatively higher mean inefficiency levels. In the 1997/98 distributions the two fisheries show more concentration in the lower inefficiency (higher efficiency) regions, with the Northern fishery mean inefficiencies being generally lower than those of the Southern fishery. A closer look at the Figure shows that in this period the two fisheries’ estimates present mulch-modal distributions for profit, technical, and allocative inefficiencies.

The kernel density is essentially a smooth version of histogram. This means that small bumps in Figure 4.6 actually depict multiple modes in the distribution. Though the modal bumps in the Southern fishery are not as pronounced as observed in the Northern fishery, there is a clear indication that there are a number of groupings of inefficiency estimates in both fisheries. With the exception of the 2000/01 and 2004/05 periods, the picture in other periods is not much different from that of 1997/98. In the 2000/01 and 2004/05 periods the profit inefficiencies for both fisheries are more concentrated around the 27-33% and 46-57% estimates for the two periods, respectively. This is higher than what is observed in all other periods.

It was earlier noted that vessels in the Northern Zone fish for between one to ten days per trip, while their southern counterparts generally undertake day trips, fishing close to their home ports. One would, therefore, expect that firms in the Southern Zone would be more profit and allocatively efficient, given their lower operational costs. However, a possible outcome of such fishing strategy could be that vessels in the Southern Zone will make more trips, on average, than those in
the Northern Zone. This means that though fishing cost in the Northern Zone may be higher than in the Southern Zone due to longer travel distance, the Northern Zone may be more allocatively efficient because on average they make less frequent trips. Further to that, a trend observed since the introduction of the quota system in the Northern Zone is that license holders fish in reduced area using the least fuel and time possible (PIRSA, 2007). Such operational strategies are likely to positively impact efficiency, particularly profit and allocative efficiency in the fishery.\textsuperscript{13} Variations in economic performance is also attributed to market performance for particular lobster types within regions in the Northern Zone (PIRSA, 2007, pp. 47-48). We further observe that whereas effort decreased in the Northern Zone between 1997 and 2007, between 2003 and 2008 effort increased in the Southern Zone by about 96%. At the same time, however, catch rate in the Southern Zone declined considerably between 2003 and 2009, as earlier mentioned. This could possibly be another underlying factor explaining the poorer efficiency performance in the Southern Zone relative to the Northern Zone. This possibility is explored in the next Chapter. Further to that, results here are indication that even though the Southern Zone faces lower costs and earn relatively higher profits, given its technology firms in this zone are not making high enough profits to be comparatively more profit efficient.

We observe that the efficiency performance in both fisheries was particularly poor in the 2004/05 period. All efficiency measures for both zones in this period were lower, compared to other periods. Given the rather poor biomass, harvest, and CUE levels in the fisheries in this period it is perhaps reasonable to say that, all else remaining constant, these factors probably affected efficiency performance of the two fisheries significantly. This is also investigated in the next Chapter. Differences in the mean and maximum scores also show that there is greater variation among firms in the

\textsuperscript{13}We do not investigate the possible effect of operational strategies in this work.
Southern Zone compared to those in the Northern Zone.

4.7 Conclusion

In the past efficiency investigations in fisheries have generally focused on productivity, technical efficiency, cost, and in some instances, revenue efficiency. Attention to profit efficiency analysis has been a more recent development. This Chapter has argued that the profit efficiency concept is superior to that of cost when evaluating overall performance of firms. Profit efficiency evaluation is an important exercise that helps to identify inefficiencies resulting from choosing suboptimal input-output mix. For these and other reasons emphasized in this Chapter, the importance of theoretical and empirical analysis of profit efficiency measures can not be ignored.

The Chapter emphasized that the South Australian Rock Lobster Fishery is an important sector of the state’s fishing industry, making significant contributions to the state’s economy. This makes the critical examination of the fishery’s economic performance crucial to evaluating the sustainability of the fishery.

This Chapter applied a new method of profit efficiency analysis to the South Australian Rock Lobster Fishery. In particular we used a combination of the Nerlovian and Directional Distance Function methods to decompose profit efficiency into its technical and allocative components. To our knowledge there are no studies that have applied these methods to investigate profit efficiency in this fishery. Previous analysis of the two fisheries, based on cost and revenues, indicate that the Southern Zone fishery is more profitable than the Northern Zone and, therefore perceived to be more profit efficient. We tested if indeed the Southern Zone fishery is more profit efficient compared to its Northern counterpart. In contrast to the perception about profit performance in the fishery we find that the Northern Zone fishery appears to
have higher profit efficiency than the Southern Zone, for the period investigated. Specifically, we showed that though operational cost in the Southern Zone is lower than is observed in the Northern Zone, on average the Northern Zone is more profit efficient than the Southern Zone.

Results in this Chapter also show that in both the Northern and Southern Zones profit efficiency can be largely attributed to allocative inefficiency, except for the 2004/05 period when technical inefficiency contributed more to profit inefficiency than did allocative inefficiency. The relatively high technical inefficiency levels in the 2004/05 period can be attributed to a number of challenges. Such challenges included significant drops in the biomass level, decline in harvest values due to exchange rate shocks, increases in effort coupled with significant drops in catch rate. These offer possible explanations to the poor economic performance in the fisheries investigated and will be examined in detail in the following chapter.

Differences in mean and maximum efficiency measures suggest that there is greater variability in economic performance in the Southern Zone than observed in the Northern Zone. On a period by period basis, the Northern Zone appear to perform better than its southern counterpart in terms of profit efficiency. These differences do not appear significant in absolute terms. However, we do not find enough statistical evidence to reject the alternate hypothesis that mean efficiency performance are different in the two zones. The uniqueness of the bootstrapping method applied in the analysis was that it helped to obtain more reliable estimates and, draw reasonable statistical inferences from the results. Although the bootstrapping method was also applied to help address the sensitivity of our methods to small sample sizes, we caution that due to small numbers, particularly in the case of the Northern Zone, these results be treated with care.

This Chapter has argued that the Nerlovian method of efficiency evaluation pos-
sesses decomposition power, together with the ability to overcome the negative profits problem, computationally. The directional distance function approach has also been shown to posses advantage over the Shephard type distance functions. It was argued, for example, that the additive nature of the profit function makes the radial Shephard type distance functions less appropriate dual model technology for profit efficiency analysis. The directional distance function, on the other hand, has been shown to allow factors to change in opposite directions. In other words, it allows simultaneous output expansion and input contraction.

A number of methods, including parametric and non-parametric, have been employed to analyze profitability and other economic performance in the past. Despite the presence of these methods consensus on the appropriate technique, in the context of profit efficiency, is yet to be achieved. For example, parametric techniques such as stochastic frontier, have been found not to be flexible when it comes to profit decomposition. Further to that, while methods such as the INPD possess strong decomposition power, their ability to overcome the negative profits problem, particularly in fisheries, still remains a drawback. A unique advantage of the Nerlovian method in this regard is that it poses no computational problem when it comes to negative profits. We acknowledge, however, that in fisheries where negative profits are a problem, the Nerlovian method may not be solving the negative profits challenge entirely. We emphasize, however, that the ability to include negative profits in the initial computations is a huge advantage of the Nerlovian method, compared to others. Finally, to further illuminate the true potential of the methods employed in this Chapter in fisheries, future work will focus on applying the techniques in other fisheries.
Chapter 5

The Role of Fixed Cost and Non-Discretionary Variables in Fisheries: A Theoretical and Empirical Investigation.

5.1 Introduction

Profit efficiency evaluation is valuable not only in identifying sources of inefficiency, but also of major interest to managers, firm owners and other stakeholders. Profit efficiency in itself is one of the major factors that can help explain firm survival and growth, as well as changes in industry structure. In fisheries a major interest to policymakers is the sustainability of the industry. This means that a critical evaluation of factors affecting profit efficiency in the industry is vital for sound policy formulation aimed at ensuring the industry’s sustainability across time.

The main objectives of this Chapter are two-fold. The first is to provide a theoretical basis to justify the need to consider the importance of vessel capital when evaluating profit efficiency in fisheries. The second is to empirically identify factors beyond firms control which can significantly affect profit efficiency.
Based on the heavy initial capital outlay, fixed cost is considered important in fisheries (Clark et al., 1979). Both large and smaller vessels are affected differently for various reasons (Grafton et al., 2006), underscoring the need to separate fixed costs from other operating costs.\footnote{\textit{\cite{grafton2006}} find that while small vessels improved their short-run technical, labour and fuel allocative efficiency, large vessels realized significant improvements in short-run economic cost efficiency.} We develop a model that allows a firm to make a long-run decision about the optimal level of variable effort and to choose the size of vessel accordingly. Once the vessel-size decision has been made, however, the firm may choose to use a sub-optimal level of variable effort with the fixed input. This sub-optimal use comes at additional variable cost but, importantly, this cost is less than the (now sunk) fixed cost. We examine the impact on biomass of the inclusion of this sunk cost component. We then generate testable empirical predictions of the effect of exogenous changes in biomass, price and vessel length on profits.

It has been pointed out in the literature that both biological and economic compositions of fisheries models are sometimes over simplified (Clark et al., 1979). It has thus become necessary to extend the biological or economic component, or both, in an attempt to show possible useful practical applications in fisheries. To do this we introduce fixed cost into the conventional profit function and modify the cost structure in the function. This enables us to carry out theoretical analysis of the full effect of firm profit maximization on fish stock. We focus on fishers’ effort choices when maximizing profits and how this affects stock levels across time. We do this using a modified version of the profit function that include a fixed input that can be used with a variable input at sub-optimal capacity, and relate the analysis to different management regimes at the same time.

The empirical analysis of non-discretionary factors affecting efficiency is conducted using truncated regression with bootstrap on data from the South Australian Rock Lobster Fishery. To our knowledge there are no studies focusing on profit efficiency
This Chapter is also the first to employ the bootstrap truncated regression approach to study the effect of non-discretionary variables on profit efficiency. A major importance of this method is its ability to correct bias generated by the deterministic data envelopment analysis (DEA) technique that computes the efficiency scores, particularly in the face of small sample sizes.

The empirical part of the Chapter adopts a semi-parametric approach by first using DEA efficiency scores calculated in the previous Chapter on variable input and regressing on non-discretionary inputs. We do this using a parametric truncated regression with bootstrap technique. We adopt this semi-parametric approach for two reasons. The dependent variable we use is pre-determined by a non-parametric DEA procedure. This non-parametric approach has been found to be serially correlated with some important underlying variables that may well explain efficiency performance. However, this is not established when DEA estimates alone are considered in efficiency analysis. Another reason is that these non-discretionary variables are fundamentally different from other input variables. These factors are considered fundamentally different from other input variables in as far as their values cannot be altered either directly by the firm or within meaningful time frame. For example, a fishing firm cannot alter its assigned fishing quota, neither can it alter the length of its vessels, in any fishing period. This means there is the need to employ other methods that can help gauge out the role of these variables in the determination of a firm’s economic performance. Our objective here is to determine if indeed such factors have any impact on profit efficiency and, how such factors affect the sustainability of the fishery under investigation. Using a parametric method to achieve this objective is consistent with the literature (for examples, see Simar and Wilson (2011) and Assaf and Matawie (2010)).

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2There are studies of rock lobster fishery profits in the region including Sharp et al. (2004)’s study of the New Zealand Rock Lobster Fishery, Hamon et al. (2009)’s study of the Tasmanian Rock Lobster Fishery, and EconSearch’s economic indicator reports on the South Australian Rock Lobster Fishery.
Our theoretical analysis suggests that though the effect of vessel size can be ambiguous, if effort is closer to optimal vessel usage profits will rise. However, profits will fall if having a larger vessel exacerbates the sub-optimality of vessel use. The theoretical analysis further shows that as long as the cost associated with sub-optimal use of vessel size remains positive but lower than the sunk costs the equilibrium stock level is negatively affected. We also show theoretically, that changes in prices have a direct and an indirect effect on profits. A rise in output price is good for profits, at least in the short-run. The indirect long-run effect of higher prices is negative through a reduction in biomass.

The empirical results suggest that increases in fish stocks are desirable for profit efficiency but only up to a point. This result is supported by our theoretical results, and consistent with the fisheries literature which indicates that incremental changes in the fish biomass though beneficial, is counter productive beyond certain point. Zone specific characteristics and the individual transferable quota (ITQ) management system are both found to impact profit efficiency positively. Finally, we find evidence to suggest that unfavourable exchange rate position of the rock lobster fishery with its major trading partners may explain some of the allocative (managerial) challenges that negatively impact profit efficiency in the fishery.

Products of the fishery are mainly for the export market and so exchange rate changes are important when considering profits in the fishery. Efficiency studies in the literature generally use either the DEA or the free disposal hull (FDH) procedures to obtain efficiency measures in a first stage. In a second stage the efficiency measures obtained in the first stage are used as the independent variable and regressed on a number of non-discretionary variables, using methods such as ordinary least square (OLS), censored, or tobit regressions. Simar and Wilson (2011), how-

\footnote{See for example, Dupont et al. (2005); Grafton et al. (2007) and Kompas et al. (2010)}

\footnote{Simar and Wilson (2007), find over 1,500 articles for the period between 2007 and 2010.}
ever, explain that the first stage measures are estimates of the unobserved true efficiency measures, and thus serially correlated in a complicated unknown way with the non-discretionary variables. The second stage is the application of various parametric methods to determine the effect of other factors, not considered in the first stage, on the efficiency scores. In the past the two stages have been considered separately. Considering the two stages together is not a requirement though it is common to find the two stages together in one paper in recent times (Simar and Wilson, 2011). We consider the two in separate but related Chapters.

Another reason for the violation is attributed to the fact that the DEA scores are relative efficiency indexes and not absolute indexes (Barros and Assaf, 2009). To obtain statistical properties of the efficiency scores obtained from the DEA procedure, Simar and Wilson (1998; 1999; 2007), propose the bootstrap method in the second stage regression. The second stage model is specified based on assumptions that lead to truncated regression which can be consistently estimated using maximum likelihood (MLE) estimation. Simar and Wilson (2007) show that these assumptions augment the standard non-parametric production model where DEA efficiency estimators are consistent to incorporate non-discretionary variables. They show the consistency of the second stage estimated results in a Monte Carlo experiment. It is also emphasized that the bootstrap method provides the only feasible means for inference in the second stage (Simar and Wilson, 2011). This view is emphasized in a recent work by Lee and Worthington (2011).

The Chapter is structured as follows. Section 5.2 sets up the theoretical model, detailing the firm’s long and short-run decisions. Management techniques and empirical predictions are also discussed in this Section. In Section 5.3 we provide theoretical exposition of the empirical method employed in the analysis, with Section 5.4 describing the data from the South Australian Rock Lobster Fishery. In
Section 5.5 the empirical results regarding the impact of non-discretionary variables on profit efficiency are presented. Section 5.6 concludes that addressing the role of capital is important in studies of fisheries profitability and provides suggestions for future extensions.

5.2 Model

In the standard dynamic, single-species fisheries Gordon-Schaefer model (Gordon, 1954; and Schaefer, 1957) fishermen face a constant marginal cost of effort which is equal to average cost. We depart from this assumption by including two inputs in harvesting: one that is variable and one that is fixed in the short-run, the latter hence having some associated sunk costs. The decision on what size of the fixed input (say, vessel length) to purchase is made to correspond with maximum profits at the optimal, ex ante, level of effort. After this decision has taken effect, however, the fishermen may find it more profitable to use the vessel at a sub-optimal capacity (either too much or too little) and pay an additional cost for this. Imagine a standard long-run average cost diagram. Suppose we are operating in the constant-returns-to-scale range so that the minimum of the short-run average cost for every vessel size is the same ($\gamma$) but that the short-run average cost curve associated with each vessel size is greater to the left and the right of the minimum than the long-run average cost curve. We compare the equilibrium levels of effort under these different assumptions about cost and consider the impact of including fixed costs on short-run biomass and profit levels.
5.2.1 Firm’s long-run decision

We start by considering fisherman $i$’s long-run decision where he chooses the level of the variable input effort ($E_{it}$) and the associated fixed input size ($V_{it}$) to maximize profit, taking the actions of other fishermen, $j$, ($E_{jt}$, $V_{jt}$, $j \neq i$) and the natural growth of the fish stock as given. Fisherman $i$’s decision problem is stated as:

$$\max_{E_{it}} \int_{0}^{\infty} e^{-st} \{ (pqB_t - c)E_{it} - \gamma V_{it} \} \, dt$$  \hspace{1cm} (5.1)$$

subject to

$$\dot{B}_t = F(B_t) - qE_{it}B_t - \sum_{j \neq i} qE_{jt}B_t$$  \hspace{1cm} (5.2)$$

$$F(B_t) = rB_t \left( 1 - \frac{B_t}{K} \right)$$  \hspace{1cm} (5.3)$$

As the optimal vessel size is chosen to minimize the costs of putting forth a particular level of effort, we let $V_{it} = E_{it}$ in this long-run decision, which implies

$$\max_{E_{it}} \int_{0}^{\infty} e^{-st} \{ (pqB_t - c)E_{it} - \gamma E_{it} \} \, dt$$  \hspace{1cm} (5.4)$$

subject to Equations (5.2) and (5.3), where profit depends on the output price ($p$), technical capability ($q$), effort level ($E_{it}$), vessel size ($V_{it}$), stock size ($B_t$), average and marginal cost of effort ($c$), and average cost of the vessel ($\gamma$). Growth of the fish stock is based on the logistic natural growth function, with an intrinsic growth rate ($r$), natural maximum stock size ($K$), and stock size ($B_t$), less the amount of
harvesting done by all fishermen. Thus, the Hamiltonian for player $i$ is:

$$
\mathcal{H} = e^{-\delta t} \left[ pqE_{it}B_t - (c + \gamma)E_{it} \right] + e^{-\delta t} \lambda_t \left[ rB_t \left( 1 - \frac{B_t}{K} \right) - qE_{it}B_t - \sum_{j \neq i} qE_{jt}B_t \right]
$$

(5.5)

Taking first-order conditions and assuming a symmetric equilibrium, the steady-state equilibrium stock level, $\tilde{B}$, equates the discount rate ($\delta$) with the return from leaving another fish in the ocean$^5$:

$$
\delta = -\frac{r\tilde{B}}{K} + \frac{r}{n} \left( 1 - \frac{\tilde{B}}{K} \right) \frac{pq\tilde{B}}{pq\tilde{B} - (c + \gamma)}
$$

(5.6)

Equation (5.6) is just the standard modified golden rule of fisheries except that there are two cost terms, $c$ and $\gamma$. The equilibrium biomass implicitly defined by Equation (5.6) gives an associated equilibrium level of effort $\tilde{E} = \frac{r}{nq} \left( 1 - \frac{\tilde{B}}{K} \right)$ and therefore the optimal vessel size ($\tilde{V}$).

### 5.2.2 Firm’s short-run Decision

Now let us consider the decision for a fisherman who has already purchased a vessel of size $\tilde{V}$ and the cost of doing so is sunk. If there were no inefficiencies associated with using the “wrong” size of vessel, that is, if the short-run average cost curve was the same shape as the long-run average cost curve (at least over some range), the short-run decision would lead to effort being determined by Equation (5.6) but with $\gamma = 0$. Suppose, however, that to use a vessel of size $\tilde{V}$ with effort $E \neq \tilde{E}$ involves some additional cost (say increased maintenance cost if $E > \tilde{E}$ or increased mooring costs if $E < \tilde{E}$):

$^5$See Appendix C, Proof 1
Suboptimal Cost \( \frac{m}{2} (E_{it} - \bar{V}_i)^2 \)

then the Hamiltonian for the fisherman’s short-run profit-maximizing decision is represented by:

\[
\mathcal{H} = e^{-\delta t} \left[ pqE_{it}B_t - cE_{it} - \frac{m}{2} (E_{it} - \bar{V}_i)^2 \right] + e^{-\delta t} \lambda_t \left[ rB_t \left( 1 - \frac{B_t}{K} \right) - qE_{it}B_t - \sum_{j \neq i} qE_{jt}B_t \right]
\]

Taking first-order conditions and assuming a symmetric equilibrium, the steady-state stock level, \( \hat{B} \), is now implicitly determined by\(^6\):

\[
\delta = -\frac{r \hat{B}}{K} + \frac{r}{n} \left( 1 - \frac{\hat{B}}{K} \right) \frac{pq \hat{B}}{pq \hat{B} - c - m \left( \frac{r}{nq} \left( 1 - \frac{\hat{B}}{K} \right) - \bar{V} \right)}
\]

Clearly if there were no costs associated with sub-optimal use \( (m = 0) \) we would have the standard modified golden rule. Under the assumption that these costs of sub-optimal use (that is, \( m \left( \frac{r}{nq} \left( 1 - \frac{\hat{B}}{K} \right) - \bar{V} \right) \)) are positive but less than the fixed costs, \( \gamma \), (at least in a neighbourhood of \( \bar{V} \)), the equilibrium stock level \( \hat{B} \) is lower than \( \bar{B} \) and effort is higher. Choosing this higher level of variable input than is optimal for the vessel size will result in lower than anticipated profits but is in the fisherman’s best short-run interests. What we would expect to observe in a fishery with fixed (and sunk) costs is lower profits and lower biomass.

### 5.2.3 Management techniques

Now let us consider the impact of different management techniques: limited entry; total allowable catch (TAC) limits; and individual quotas (IQs). Limited entry

\(^6\)See Appendix C, Proof 2.
simply fixed the number of fishermen \((n)\) and thus in our model we would observe the lower biomass and the associated lower profits in the presence of fixed costs.

Management techniques in fisheries are often simply aimed at addressing the overcapacity problem, via reduction in labour and capital inputs to levels where marginal cost of an additional increase in effort equals the corresponding marginal revenue generated (Owers, 1975). In the absence of overcapacity control firms will expand effort to the point where economic rent is zero. The firm also makes its production decision on the resource stock but behaves as though the resource has a zero user cost (Gordon, 1954).

If the objective is to ensure sustainability of the biomass and controlling capacity is not enough, catch limits are frequently introduced. The TAC management system, for example, requires that the fishery is shut down when allowable harvest has been taken. The assumption is that TAC programme is perfectly enforceable, such that fishing is stopped whenever the set TAC level is reached. The perfect enforceability of TAC implies a biological equilibrium at stock sizes where growth equals the TAC (Anderson and Seijo, 2010). The literature, however, acknowledges that the introduction of TAC has not succeeded in solving the open access problem of over fishing. Instead TAC has made the over capacity problem more severe as a result of Olympic-type of fishing and, consequently, dissipating resource rents in most cases (Asche et al., 2008). This manifests in our model where the TAC may be able to implement stock level \(\hat{B}\) but each fisherman will then face incentives to pay at least the cost \(m\) and overuse his vessel in the race for the fish.

An individual quota system is one of the alternative techniques introduced in a number of fisheries to address the overcapacity problem. This management technique is expected to reduce effort, increase efficiency and ensure sustainability of

\footnote{Olympic-type fishing occurs when fishers (with or without licenses) are given the right to harvest until the specified TAC is taken.}
the fisheries. The ITQ system is also thought to have the potential to reduce cost, and change revenues of fishing firms over both the short and long-run. Increased returns in Halibut fishing in Canada, for instance, is found to far exceed cost with the introduction of individual vessel quotas, IVQs (an IQ system) (Grafton et al., 2000). In our model, an IQ system may be able to not only implement $\hat{B}$ (or, more, preferably the socially optimal level) but also to provide the incentive to use the vessel at its optimal capacity.

5.2.4 Empirical predictions

One purpose of conducting this theoretical analysis is to inform the empirical analysis in subsequent Sections. In the previous Chapter, profit inefficiency measures were calculated based on a long-run assumption where all inputs are variable. The theory here indicates that non-discretionary (in the short-run) components of profits - biomass, output price, and vessel size - may play an important role. To see this specifically, we can consider some simple comparative statics. Recall that in each period individual profits (excluding sunk costs) will be:

$$\hat{\pi} = pq\hat{B} - c\hat{E} - \frac{m}{2}(\hat{E} - \hat{V})^2$$

(5.9)

At the symmetric steady-state the growth rate equals the harvest so $\hat{E} = \frac{r}{nq} \left(1 - \frac{\hat{B}}{K}\right)$ so:

$$\hat{\pi} = (pq\hat{B} - c)\frac{r}{nq} \left(1 - \frac{\hat{B}}{K}\right) - \frac{m}{2} \left(\frac{r}{nq} \left(1 - \frac{\hat{B}}{K}\right) - \hat{V}\right)^2,$$

(5.10)

and thus, the response of profits to an exogenous increase in biomass can be calculated as:
\[
\frac{d\hat{\pi}}{d\hat{B}} = \frac{r}{nqK} \left[ \left( pqK - c - m(\hat{E} - \hat{V}) \right) - 2 \left( pq\hat{B} - c - m(\hat{E} - \hat{V}) \right) \right] \] (5.11)

which is positive in the relevant range.\(^8\) Note that Equation (5.11) is increasing in \(c\): increasing biomass is more helpful (to increase profits) for higher cost firms. Note also that the relationship between profits and biomass is increasing at a decreasing rate.\(^9\)

The response of profits to an exogenous increase in output price (through an appreciation of the Australian dollar for example) can be calculated as:

\[
\frac{d\hat{\pi}}{dp} = q\hat{B} \frac{r}{nq} \left( 1 - \frac{\hat{B}}{K} \right) + \frac{\partial \hat{\pi}}{\partial \hat{B}} \frac{d\hat{B}}{dp} \] (5.12)

As can be seen from Equation (5.12), the effect of price on profits is made up of a short-run effect and a long-run effect via biomass. In the short-run, an increase in price is good for profits but in the long-run the effect is ambiguous because the higher price induces increased effort which negatively impacts the biomass and hence harvest will fall.\(^{10}\) The overall impact of the price versus quantity effect is ambiguous. As the data we use in the analysis here is for four distinct time periods, and we will control directly for biomass, the short-run (positive) effect is what we would expect to observe in the data.

The response of profits to an exogenous increase in vessel size can be calculated as:

\[
\frac{d\hat{\pi}}{d\hat{V}} = m(\hat{E} - \hat{V}) + \frac{\partial \hat{\pi}}{\partial \hat{B}} \frac{d\hat{B}}{d\hat{V}} \] (5.13)

\(^8\)See Appendix C, Proof 4.
\(^9\)See Appendix C, Proof 4.
\(^{10}\)See Appendix C, Proof 5 and Equation (5.11).
As can be seen from Equation (5.13), the effect of having a larger vessel is ambiguous in both the short- and long-run. The initial impact depends on whether effort is already above or below optimal for vessel size $\tilde{V}$: if having an exogenously larger vessel means the effort is closer to the optimal for that vessel size, profits will rise; or profits will fall if having a larger vessel exacerbates the sub-optimality of effort. The long-run impact, via the effect on biomass, is negative which may counteract or reinforce the initial impact.\footnote{\footnotetext{See Appendix C, Proof 5 and Equation (5.11).}} In this theoretical characterization we have been looking for the steady-state, we have not looked at the dynamics of going from a initially unexploited fishery to a mature fishery.\footnote{Clark et al. (1979) show that if capital is at least partially malleable the steady-state will be the same but that the dynamics of getting to the steady-state will be different from the case of perfectly malleable capital.} If we think that the fishery considered in our empirical analysis is now mature and that vessels were purchased when the biomass was closer to its original size, we would expect that the vessels are larger than is now optimal and hence we would expect larger vessels to experience lower profits in both the short- and long-run.

### 5.3 Truncated Regression with Bootstrap

Simar and Wilson (2007) propose a bootstrap semi-parametric procedure for making valid inferences about the impact of non-discretionary factors on efficiency measures. The procedure is outlined in the form of algorithms, the first of which is referred to as algorithm 1. This algorithm details a single bootstrap procedure. A double bootstrap procedure was later proposed (Simar and Wilson, 2007). However, they show that the single bootstrap and double bootstrap procedures produce similar results. Olson and Vu (2009) confirm this in their study on economic efficiency in farm households, investigating factors explaining differences in economic efficiency.
We adopt the single bootstrap procedure in this Chapter. In this approach we regress the profit efficiency scores obtained in our first study on non-discretionary factors using a truncated regression with bootstrap. In the next few paragraphs we give a brief description of the bootstrap concept, its importance in the second stage analysis and, give details of the bootstrap algorithm used in this Chapter. We also detail the application of the truncated regression method used in the next Section.

Bootstrapping is a re-sampling method which re-samples the data with replacement. The idea is to mimic the data generating process (DGP) characterizing the underlying true data generation. The procedure helps provide confidence intervals for the regression parameters. Details of this are discussed later in this Section. Since the DEA scores are simply measures of distance to a best practice frontier a number of questions arise. Simar and Wilson (2011), for example, identify questions such as: how far might a new firm lie beyond the best practice frontier, if such a possibility exists; by how much are observed firms able to improve their performance, if they are able to do so; or by how much can firms on the best practice frontier able to improve their performance, assuming they are able to do so. They emphasize that statistical inference is important, and meaningful inference require coherent, well-defined statistical model describing the DGP and providing probabilistic structure for inputs, outputs, and non-discretionary (environmental) variables. The bootstrapping method employed in this Chapter uses the single bootstrapping procedure.

The Farrell (1957) efficiency measure is assumed to take a functional form, \( \psi(Z_i, \beta) \), of the non-discretionary co-variates, \( Z_i \), and the parameters, \( \beta \), together with an independently distributed error term, \( \varepsilon_i \), assumed to represent the part of inefficiency unexplained by the co-variates (Simar and Wilson, 2007). Given that by definition the inefficiency measure is greater than or equal to unity, that is \( \theta_i \geq 1 \), Simar and
Wilson (2004) make the assumption that the error term, $\varepsilon_i$, is independently and normally distributed random variable with mean 0, and unknown variance $\sigma^2_\varepsilon$, i.e., $\varepsilon_i \sim N(0, \sigma^2_\varepsilon)$, with left truncation at $1 - \psi(Z_i, \beta)$. These assumptions imply the following equation:

$$\theta_i = \psi(Z_i, \beta) + \varepsilon_i \geq 1 \quad (5.14)$$

Equation (5.14) is understood to be the first-order approximation of the unknown true relationship (Simar and Wilson, 2004). Here $\theta_i$ can be considered as the true estimate of the unobserved true efficiency measure, and $\psi$ a smooth continuous function. Equation (5.13) can also be re-arranged to yield $\varepsilon_i \geq 1 - \psi(Z_i, \beta)$. This explains why the error term, $\varepsilon_i$, is truncated on the left at $1 - \psi(Z_i, \beta)$. It must be emphasised that the left-truncation arises from the fact that the true inefficiency measure, $\theta$, is unknown (or not observed) and so is it’s error term, $\varepsilon$. The assumptions imply a separability condition, where separability here is used to mean that the support of the output variables does not depend on the non-discretionary variables, $Z$. The functional form, $\psi(Z_i, \beta)$, is also assumed to be linear. The linearity assumption is made to correspond with what is typically observed in the literature. For details see Simar and Wilson (2007). Though different parametric forms, for example logistic regression, can be assumed, we follow the convention in the literature and assume linear form. Ramalho et al. (2010) note that given the interpretation of the DEA scores, the scores can be treated like any other dependent variable in the regression analysis. This implies that the parametric estimation and inference in the regression analysis can be carried out using standard procedure.\(^\text{13}\)

The single bootstrapping procedure essentially requires regressing the DEA effi-

\(^{13}\)McDonald, 2009; and Romalho et al., 2010, interpret the DEA scores as descriptive measures and, therefore, the frontier can be viewed as observed best-practice construct within the selected sample (Simar and Wilson, 2011).
ciency scores on non-discretionary variables using truncated regression of the form:

\[ \hat{\theta}_i = Z_i\beta + \varepsilon_i \geq 1 \]  

(5.15)

The variables, parameters and error terms are as explained in Equation (5.14). The left hand side dependent variable, \( \hat{\theta}_i \), is the computed efficiency scores replacing the true unobserved efficiency measures in Equation (5.14). Simar and Wilson (2007) explain that \( \hat{\theta}_i \) is an estimate of the unobserved true efficiency measure, \( \theta_i \), and thus serially correlated in a complicated, unknown way with the non-discretionary variables. Further to that, under the assumption that the DEA efficiency estimates obtained are consistent, the maximum likelihood (ML) estimation of Equation (5.15) yields consistent estimates of \( \beta \). However, given that the estimates have just replaced the true unobserved efficiency measure \( \theta_i \), inference from Equation (5.15) is problematic. This is so because while \( \hat{\theta}_i \) estimates \( \theta_i \) consistently, DEA estimators have a slow convergence rate and are biased (Simar and Wilson, 2007).\(^{14}\) The single bootstrap procedure is therefore proposed to help overcome these problems. The bootstrap procedure for the truncated regression incorporates information on the parametric structure of Equation (5.15), and the distributional assumption on the error term.

Now we provide details of the algorithmic procedure of the Simar and Wilson (2007) single bootstrap method. The algorithm follows the following steps. The first step involves the computation of the efficiency scores. As mentioned before, this Chapter uses efficiency scores computed in a separate Chapter. This was done using the non-parametric DEA approach. Mean distributions of these efficiency scores are provided in Table (5.1). These are mean scores for the Northern and

\(^{14}\)It is assumed that the data generating process meets the conditions for the law of large numbers to apply, so that the empirical moments can be assumed to converge in probability to their expectation. The rate of convergence is thus considered one of the factors of the efficiency of the method (Simar and Wilson, 2007).
Southern Zone Rock lobster Fisheries of South Australia, covering the periods; 1997/98, 2000/01, 2004/05, and 2007/08. The second step involves estimation of the parameters, $\hat{\beta}$ and $\hat{\varepsilon}_i$, of Equation (5.15). This is done using the ML method to estimate Equation (5.15) as a truncated regression. The next step computes $B$ bootstrap estimates of $\hat{\beta}$ and $\hat{\sigma}_\varepsilon$ as follows: (i) for each observation $i = 1, \ldots, n$, $\varepsilon_i$ is drawn from a normal distribution with variance $\hat{\sigma}_\varepsilon^2$ (i.e., $N(0, \hat{\sigma}_\varepsilon^2)$) with left truncation at $(1 - Z_i\hat{\beta})$ and $\theta_i^* = Z_i\hat{\beta} + \varepsilon_i$ is computed; (ii) a truncated regression of $\theta_i^*$ on $Z_i$ is then estimated using ML method to give the bootstrap bias corrected estimates, $\hat{\beta}^*, \hat{\sigma}_\varepsilon^*$. The procedure also constructs the confidence intervals for the parameters together with the associated p-values (Afonso and St Aubyn, 2005). The following Section describes the data used in the analysis.

5.4 Data Description

Data on the South Australian Northern and Southern Zone Rock Lobster Fisheries were obtained from EconSearch and SARDI. EconSearch collects confidential survey data from fishing operators in the Northern and Southern Zone fisheries for the estimation of various economic indicators. The data are cross-sectional, covering the fishing periods 1997/98, 2000/01, 2004/05, and 2007/08. The fishing periods correspond with the fishing seasons in these fisheries. The Northern and Southern Zone fishing seasons fall within the financial year calendar. However, the fisheries are closed for about six months in each lunar year. The seasonal closures coincide with the breeding seasons of the fisheries. In the Northern Zone fishery is closed from the 31st of May to the 1st of November, each year. In the Southern Zone the closure is from the 31st of May to the 1st of October, each year. \textsuperscript{15} The surveys

\textsuperscript{15}We are most grateful to Stacey Paterson of EconSearch for providing us with this additional information.
are voluntary, and due to legal reasons no identifiers are used. It is therefore not possible to track individual vessels over time. For each of these time periods the data are grouped separately into Northern (NZ) and Southern (SZ) Zones. The data are further grouped into discretionary (direct variable, quasi-fixed and fixed costs) and non-discretionary categories. In this Chapter we focus on the non-discretionary variables.

The non-discretionary variables include; estimated biomass levels, boat length, boat age, engine age, and electronic equipment age. In the context of fisheries these variables are considered fundamentally different from other input variables in as far as the values cannot be altered either directly by the firm or within meaningful time frame. For example, under a non-transferable individual quota system a fishing firm cannot alter its fishing quota assigned in any given period, nor can it alter the length of its fishing vessel within a single fishing period. Note: quotas are assigned based on TAC which is in turn determined by the biomass level in each period. Mean values of these variables, including their standard deviations, minimum and maximum variables, for all the periods under investigation are provided in Table 5.1. The biomass mean values are significantly higher in the Southern Zone than in the Northern Zone, in all periods. Observe that though mean biomass is higher in the Southern Zone, there is greater variability in the Southern Zone biomass levels, compared to the North. It is important to note that though there was consistent decline in the Northern Zone biomass throughout the periods, the fall was sharpest in the 2004/05 fishing period. The Southern Zone, on the other hand, experienced a significant increase in biomass levels in 2000/01 and thereafter registered its first decline in 2004/05. The fall in the Southern Zone, however, was steeper in the 2007/08 period.

For the 1997/98 and 2000/01 periods the mean boat age in the Southern Zone is higher than in the North. The opposite is the case for the 2004/05 and 2007/08
Table 5.1: Period by Period Means, Standard deviations, and Spread of Efficiency and Non-discretionary Variables

<table>
<thead>
<tr>
<th>Period</th>
<th>Zone</th>
<th>Ineff. measure (θ)</th>
<th>Biomass</th>
<th>Boat age</th>
<th>Boat length</th>
<th>Engine age</th>
<th>Elect. Equip. age</th>
<th>HKD/AUD Exch. rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997/98</td>
<td>NZ</td>
<td>1.32 (0.26)</td>
<td>2912.04 (75.81)</td>
<td>11.78 (6.05)</td>
<td>10.27 (0.66)</td>
<td>6.56 (4.54)</td>
<td>4.47 (2.24)</td>
<td>5.28 (0.34)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[1.02, 1.83]</td>
<td>[2858.43, 2965.64]</td>
<td>[3.00, 23.00]</td>
<td>[8.42, 11.36]</td>
<td>[1.00, 15.00]</td>
<td>[2.00, 11.00]</td>
<td>[4.53, 5.85]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.30 (0.34)</td>
<td>2911.72 (337.00)</td>
<td>12.82 (6.97)</td>
<td>11.94 (0.90)</td>
<td>7.28 (7.08)</td>
<td>4.54 (1.26)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SZ</td>
<td>[1.02, 2.70]</td>
<td>[2673.43, 3150.01]</td>
<td>[3.00, 30.00]</td>
<td>[9.90, 13.24]</td>
<td>[1.00, 30.00]</td>
<td>[3.00, 7.00]</td>
<td></td>
</tr>
<tr>
<td>2000/01</td>
<td>NZ</td>
<td>1.42 (0.22)</td>
<td>2351.06 (214.29)</td>
<td>10.38 (6.14)</td>
<td>10.24 (0.78)</td>
<td>5.13 (2.82)</td>
<td>5.25 (1.89)</td>
<td>4.20 (0.22)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[1.03, 1.82]</td>
<td>[2199.53, 2502.58]</td>
<td>[2.00, 30.00]</td>
<td>[7.54, 11.09]</td>
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<td>[2.00, 10.00]</td>
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<tr>
<td></td>
<td></td>
<td>1.42 (0.25)</td>
<td>4510.75 (342.01)</td>
<td>14.42 (8.42)</td>
<td>11.89 (1.16)</td>
<td>5.22 (4.93)</td>
<td>4.62 (3.71)</td>
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<td>[1.00, 19.00]</td>
<td>[1.00, 15.00]</td>
<td></td>
</tr>
<tr>
<td>2004/05</td>
<td>NZ</td>
<td>1.83 (0.52)</td>
<td>1716.14 (30.31)</td>
<td>19.50 (12.35)</td>
<td>10.19 (0.91)</td>
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<td>5.79 (4.02)</td>
<td>6.13 (3.90)</td>
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<td>[1.00, 24.00]</td>
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<tr>
<td>2007/08</td>
<td>NZ</td>
<td>1.53 (0.58)</td>
<td>1475.04 (83.49)</td>
<td>21.83 (12.03)</td>
<td>10.16 (0.94)</td>
<td>6.26 (8.00)</td>
<td>3.09 (3.67)</td>
<td>6.99 (0.31)</td>
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<td>[6.10, 7.52]</td>
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<td></td>
<td>1.73 (0.83)</td>
<td>2534.33 (704.14)</td>
<td>16.67 (10.97)</td>
<td>11.83 (1.26)</td>
<td>6.73 (5.16)</td>
<td>4.04 (3.44)</td>
<td></td>
</tr>
<tr>
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<td>[5.00, 66.00]</td>
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<td>[1.00, 26.00]</td>
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</tbody>
</table>

Notes: Biomass is in tonnes; Boat age, Engine age, and Electrical equipment age, are all in years; and Boat length, in meters. Ineff. measure ($\hat{\theta}$), refers to profit inefficiency measures. Period, refers to fishing periods considered for the study, with days referring to trading days in each financial year.

Data sources: EconSearch (2011), and Reserve Bank of Australia (2013).
On the other hand, mean engine age is generally higher in the Southern Zone, except for the 2004/05 period. A similar picture is observed for electrical equipment age, where the mean age is higher in the Southern Zone for all periods except for the 2007/08 period. Mean boat length is higher in the Southern Zone for all periods. The mean values of other non-discretionary variables in the 1997/98 period for the Northern Zone are also generally lower compared to those of its Southern counterpart. The differences in the mean distributions across the zones are assumed to account for regional differences, and therefore used as non-discretionary variables in the truncation regression analysis carried out in this Chapter. In Table 5.1 are also statistics of the efficiency scores used as dependent variables. Recall from Section 5.3 of this Chapter that by definition the inefficiency measure is greater than or equal to one. Note that the efficiency scores obtained in Chapter 4 are between 0 and 1, so we specify $\hat{\theta}$ (see Section 5.3) as their inverse. This is further explained in Section 5 where the truncated regression model is specified. As you will recall from Chapter 2, these are zone specific period inefficiency scores and so we do not compare across zones. However, notice that variabilities within zones differ.

We also include the Hong Kong/Australian exchange rates (HKD/AUD) as a non-discretionary variable, for the period under consideration. The inclusion of this variable in our data set is important. According to EconSearch annual reports, unfavourable exchange rate position of the Australian dollar (AUD) in relation to the Hong Kong (HKD) dollar negatively impacts profits in the fisheries since products from these fisheries are mainly for the export market. Hong Kong is the major export destination of products from these fisheries, accounting for over 80% of total trade volume (EconSearch, 2011).  

A careful observation of the statistics}

\footnote{The exchange rate data was obtained from the official website of the Reserve Bank of Australia (www.rba.gov.au/statistics/hist-exchange-rates/). These were daily trading rates from which we calculated annual (financial year; 1st of July to 30th of June) averages, together with other statistics, for the periods covered in}
in Table 5.1 shows an appreciation of about 20% of the HKD against the AUD, between the 1997/98 and 2000/01 periods, but thereafter fell sharply by about 40% in value against the AUD in the 2004/05. This depreciation of the HKD against the AUD continued into the 2007/08 period. The fall in value between the 2004/05 and 2007/08, however, was about 19%. The appreciation of the AUD against the HKD meant that products from the fisheries had become relatively costly, with the shock in the 2004/05 period being more severe. The appreciations of the AUD against the HKD are much higher when the maximum values are considered. In a competitive world market, this shock is more than likely to have negative impact on demand for the products from these fisheries and hence profits. In the next Section we detail the empirical procedure and present the results together with the analysis. Having detailed the theoretical background of the analysis and described the data used, the next task is to describe the empirical application and analyse the results obtained. We do these in the next Section.

5.5 Empirical Application, Results and Analysis

To investigate the possible effects of non-discretionary variables on profit efficiency of the fishing firms in the South Australian Rock lobster Fishery, we specify a truncated regression model based on Equation (5.15). Reasons for using the truncated regression approach are well elaborated in the introduction to this Chapter so the details are not repeated here. However, a brief reminder of why we use the truncated regression model is in order. OLS and other methods have been shown to bias the results since the explanatory variable, the DEA efficiency scores, is likely to be correlated with the error term. This bias is avoided by running the truncated
regression based on MLE. We begin this section by describing the application procedure, show the results, and provide detailed analysis of these results.

5.5.1 Application

The non-parametric DEA technique was used in a separate but related Chapter to obtain profit efficiency scores for sampled fishing firms from the Northern and Southern Zones of the South Australian Rock lobster Fishery.\(^\text{17}\) The firms were sampled for the 1997/98, 2000/01, 2004/05, and 2007/08 fishing periods. For the regression analysis we pool the efficiency scores for the four periods together. The efficiency scores are between 0 and 1 so we specify \(\hat{\theta}_i\) as their inverse, yielding values greater than or equal to 1, i.e. \(\hat{\theta}_i \geq 1\). Using \(\hat{\theta}_i\) as the regressand, we specify the truncated model for the Northern and Southern Zone fisheries, in the form of Equation (5.15), in Equation (5.15) as follows:

\[
\text{Profit Efficiency}_{izt} = \psi(Biomass_{zt}, Biomass^2_{zt}, Boat Age_{izt}, Boat Length_{izt}, Zone Dummy_{zt}, Management (ITQ)_{zt}, Period Dummy, Engine Age_{izt}, Electrical Equipt. Age_{izt}, AUD/HKD_t) + \varepsilon_i
\]

The dependent (explained) variable is the efficiency score of firm \(i\) in zone \(z\) in period \(t\). Recall that these are inefficiency measures truncated at 1 from below (left truncation). This means that a negative coefficient on the explanatory variables indicates decrease in inefficiency hence improvement in efficiency. The opposite is

\(\text{Table 5.1, provides summary statistics of the efficiency scores used in this Chapter as the dependent variable (}\hat{\theta}_i).\)
true for a positive coefficient; that is, a worsening of inefficiency. The time subscript $t$ represents specific fishing periods and not continuous time. We specify four models using the above explanatory variables. In model (1), our base model, we include biomass, biomass$^2$, boat age, boat length, Zone dummy (i.e., NZ = 1, SZ = 0), Management (ITQ) dummy, and Period(2004/05) dummy. We include biomass$^2$ in order to observe the effect of marginal changes in the stock level. To capture zone specific characteristics we also include zone dummy to estimate the zone fixed effect. In this sense the zone dummies are used as proxies for geographical, environmental, and ecological characteristics considered fixed for each zone.

The individual transferable quota system was introduced in the Northern Zone fishery in the 2003/04 fishing period, exactly ten years after its introduction in the Southern Zone. We believe it is important to investigate any possible impact this management policy could have on profit efficiency and so include the management (ITQ) dummy variable to carry out this investigation. For reasons explained in detail later, we also include a dummy for the 2004/05 as a control variable.

Recall that our dependent variable is from pooled observations. This, however, often has the non-identical distribution problem. This occurs because the underlying population of pooled cross-sectional observations may have different distributions in different time periods (Wooldridge, 2009). The literature indicates that the problem can be solved by allowing the intercept to differ across periods. To do this we introduced period dummies for three of the four periods, omitting one period at a time as the base period. Possible variabilities among firms in the fisheries ideally require that firm specific characteristics (firm fixed effect) are controlled for. However, we are unable to do this for a couple of reasons. It was earlier mentioned that due to confidentiality reasons the observations in our data set do not have unique identifiers, and so was impossible to identify individual firms across different time periods. This limitation of the data made it impossible to include firm fixed effects.
in our models. A possible way of going around the problem was to try creating cohorts among the observations using some specific, relatively time invariant, variable such as boat length. This also proved difficult to do as boat lengths could not be tracked across different time periods.

As robustness check we specify three other models; that is, models (2), (3), and (4). In model (2) we control for engine age and electrical equipment age. We drop these variables in model (3) and include the Hong Kong/Australian exchange rate variable. We include all ten variables in model (4). As earlier explained the Hong Kong/Australian exchange rate variable was included to capture any allocative inefficiencies arising from possible management challenges caused by the exchange rate changes on the fisheries’ export markets.\textsuperscript{18} We run all the models using 2000 bootstrap replications, on Stata. This number of replications is enough to provide adequate coverage of the confidence intervals (Simar and Wilson, 2004). In the Section that follows we present results of the models together with their analysis.

\subsection*{5.5.2 Results and analysis}

Table 5.2 below presents results of the various models estimated. All four models show that increases in current levels of the fish stock, in the fisheries, are desirable. The biomass is significant across all four models at the 10\% level and in the anticipated direction; increases in biomass levels significantly increase profit efficiency levels (decreases profit inefficiency) in the fisheries. The biomass\textsuperscript{2}, on the other hand, shows that marginal increases in the biomass, after a certain point, is counter productive to profit efficiency in the fisheries. This explanatory variable is significant at the 10\% level across all four models, except for model (2), though the

\textsuperscript{18} Products from these fisheries are mainly for the export market (EconSearch, 2011).
magnitude of the coefficient are quite close to each other. The direction of both the biomass and the biomass$^2$ is consistent with the fisheries literature; monotonic increases in the biomass is desirable only up to a point (Dupont et al., 2005; Grafton et al., 2007; and Kompas et al., 2010), beyond which any incremental changes in the biomass is counter productive. This is supported by our theoretical analysis that the response of profits to an exogenous increase in biomass is positive in a given range. Boat age is not significant across all four models, however, the direction and size of the coefficient is worth mentioning. The coefficient suggests that an increase in the age of boats in the fisheries, by one additional year, is likely to reduce profit inefficiency (increase profit efficiency). A possible interpretation of this is that boat age is possibly a proxy for crew experience, which comes with the number of years the crew remains in the fisheries. In other words, if a boat is operated by the same core crew, then it is expected to gain more operational (technical) experience with each additional year, which is beneficial for efficiency. We find evidence in the literature to support this view (see Pascoe and Coglan, 2002).
<table>
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<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
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<td>-7.462*</td>
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<td>(4.639)</td>
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<td>2.700**</td>
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<td></td>
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<td>(8.633)</td>
<td>(7.572)</td>
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<tr>
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<td>1.035***</td>
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<td>337.179</td>
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<td>269</td>
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<td>269</td>
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</table>

Note: Bootstrap standard errors in parentheses, *** p<0.01, ** p<0.05, * P<0.10  
HKD/AUD: Hong Kong/Australian dollar exchange rate. Bootstrap replications: 2000  
Source: Authors’ calculations

Boat length is significant at the 10% level in all but one model, model (4), with the magnitude and direction of the coefficient being similar across all the models. The direction of the coefficient is as expected and consistent with the literature. The coefficient on this variable shows that any additional increase in boat length is
not beneficial to the profit efficiency. It was earlier noted that differing vessel sizes may have different impacts for various reasons (see for example, Tingley et al., 2005; Grafton et al., 2006; and Pascoe and Robinson, 2008). Recall from Table 5.1 that the biomass in the two fisheries declined consistently over the period, with the Northern Zone experiencing sharper declines. The implication is that the average boat length, of boats in the fisheries, was not commensurate with the biomass level and, therefore, impacted profit efficiency negatively. Results in Table 5.2 also show that holding all else constant zone characteristics affect profit efficiency positively; that is, zone characteristics increase profit efficiency (decrease inefficiency) significantly, at the 10% level in all four models. Results from models (1) and (4) show that the introduction of the ITQ management system had a positive effect on profit efficiency in the fisheries, and this was significant at the 10% level. Though not statistically significant in the other models, the direction is the same across all models, with relatively small differences in magnitude. This seems to confirm studies in the literature that point to the benefits of the introduction of the ITQ system in fisheries across the globe. Next we analyze the period variable. The above analysis is supported by our theoretical analysis in Subsection 5.2.4. The analysis suggests that though the effect of vessel size can be ambiguous, if effort is closer to optimal vessel size profits will rise. However, profits will fall if having a larger vessel exacerbates the sub-optimality of vessel use. The theoretical analysis further shows that as long as the cost associated with sub-optimal use of vessel size remains positive the equilibrium stock level is negatively affected. This is so given that effort is higher in that case. This means vessel size may affect profitability via two channels. The first is the reduction in profit levels in direct relation to vessel size. The second is the reduction in profitability in relation to reduced biomass levels caused indirectly by positive cost associated with sub-optimal use of vessel size. These offer further explanation to results obtained in our empirical analysis.
To account for possible variations in the distribution of the observations in the underlying population across different time periods we tried to incorporate the four periods into our models, as earlier explained. In all the options investigated, that is including all the periods in various ways as discussed earlier, only the versions with the 2004/05 period showed consistency and with significance at the 5% level. We also tried to incorporate time trend in the models in order to eliminate any possibility of spurious regression between profit efficiency and some of the explanatory variables such as boat age, engine age, electrical equipment age, etc. Spurious regression refers to a regression that shows significant results due to the presence of unit root in the variables. Allowing for time trend explicitly considers the possibility of changes in profit efficiency (i.e., either increases or decreases) over time for various reasons essentially unrelated to the other variables in the regression analysis (see Wooldridge, 2009). A possible reason for not picking the time trend effect in the models with time is that biomass changes may not necessarily correspond with time, and that other factors besides time are more important. In fact, in reality, as far as the fisheries under investigation are concerned, factors such as weather, ocean currents, ecological conditions, and others, may play more important role in biomass changes. Again, in order to verify if the effect of the biomass (our key dependent variable) showed significant changes over specific periods, we tried to incorporate biomass and period interaction terms. Again in all the cases, only the interaction with the 2004/05 period turned out to be significant. Results of the versions described here are not included in Table 5.2.

Another reason for keeping the 2004/05 period dummy was the peculiarity of this time period in terms of the efficiency levels and biomass changes observed in this period across the two fisheries.\(^{19}\) For example, the Southern Zone witnessed its first and sharp fall in biomass levels in the 2004/05 period, after a series of increases.

\(^{19}\)Refer to mean efficiency estimates for the two fisheries across all four periods under discussion in Table 5.1
in previous periods. For the Northern Zone though decline in the biomass was consistent, the first significant decline was registered in this time period. The efficiency estimates also suggest that the 2004/05 period presented the worst efficiency scores, relative to other periods. These factors meant that the 2004/05 needed a more rigorous investigation. Indeed results from all four models show that, relative to all other periods, the 2004/05 period negatively impacted profit efficiency, and this negative impact was significant at the 5% level. Other non-discretionary variables in the fisheries included in models (2 and 4), such as engine age and electrical equipment age were, individually and jointly, neither statistically nor economically significant.

As earlier mentioned the variable HKD/AUD was included in the analysis to help capture any other possible causes of allocative inefficiency in the fisheries over the period under investigation. Though this variable turned to be statistically not significant it provides reasonable economic insight. The coefficients of this variable in models (3) and (4) show that unfavourable changes in exchange rate position of the Australian dollar against that of a major trading partner such as Hong Kong does indeed negatively impact profit efficiency. This observation is confirmed in EconSearch annual reports. Further to that, we show in our theoretical analysis that instantaneous changes in prices do have instantaneous effect on profits. In model (4) we include all ten variables but our results do not show any significant changes compared to others, with the exception of the 2004/05 dummy variable which becomes statistically stronger at the 1% level. In fact, the AIC measures shows that this model is worst among all four. Further to that our base model, model (1), tends to be robust with the best AIC measure.
5.6 Conclusion

Profit efficiency is one of the major factors that can help explain firm survival and growth, as well as changes in the industry structure. In fisheries where sustainability is of major interest to policy makers, critical evaluation of factors affecting profit efficiency is of vital importance to sound policy formulation aimed at ensuring industry sustainability across time. The main objectives of this Chapter were two-fold. The first was to provide a theoretical basis to justify the need to consider the importance of vessel capital when evaluating profit efficiency in fisheries. The second was to empirically identify factors beyond firms control which can significantly affect profit efficiency in fisheries. The empirical analysis was conducted using a truncated regression with bootstrap on profit efficiency measures from the South Australian Rock Lobster Fishery.

This Chapter used a modified version of the cost structure to theoretically analyse the effect on profits and fish stocks. We did this by introducing a fixed input, as well as a variable input, into a conventional fisheries profit function and carried out the analysis under both the short- and long-run firm decisions. In an industry where fixed costs are considered non-malleable, the examination provides interesting theoretical insights into the significance of such costs in profit analysis in both the short- and long-runs.

Our theoretical analysis suggests that though the effect of vessel size can be ambiguous, if effort is closer to optimal vessel size profits will rise. However, profits will fall if having a larger vessel exacerbates the sub-optimality of effort use. The theoretical analysis further shows that as long as the cost associated with sub-optimal use of vessel size remains positive but less than fixed costs the equilibrium stock level is negatively affected. This is from the higher effort in that case. This means vessel
size may affect profitability via two channels. The first is the reduction in profit levels in direct relation to vessel size. The second is the reduction in profitability in relation to reduced biomass levels caused indirectly by positive cost associated with sub-optimal use of vessel size.

We also show, theoretically, that increases in prices are good for profits in the short-run, but there is an offsetting indirect, long-run negative effect via biomass. This confirms the negative price effect observed in our empirical results which can be attributed to a short-run negative effect resulting from unfavourable exchange rate shocks in the periods considered for the study. We find evidence to suggest that unfavourable exchange rate position of the rock lobster fishery with its major trading partners may explain some of the allocative (managerial) challenges that negatively impact profit efficiency in the fishery. The theoretical model also allows us to examine the effect of an exogenous increase in biomass. We find, as with the larger fisheries literature, that greater biomass will increase profits. We also find that increasing biomass has a positive effect on profits, but at a decreasing rate. Our empirical results support this theoretical observation. Empirically we also examined the impact of having an ITQ management system and found that it had a positive impact on profit efficiency. The ITQ effect is found to generally agree with existing literature on the benefits of the ITQ introduction in fisheries.

Based on Clark et al. (1979) and other assertions on the importance of vessel size in the literature, we argued that there is an overarching need to clearly separate cost of fishing vessels from other operating costs when analysing profits of fishing firms. We have also argued that this separation enables the effect of such costs on both the biomass and sustainability of the industry to be explicitly assessed. In the past some studies have examined firm profits in both fisheries (Smith, 1969; Anderson, 2000) and residential real estate (Anderson et al., 2000), under different
assumptions. However, we are yet to identify studies that analyse the impact of firm profit maximizing behaviour on fish stocks, in both the short and long runs, using a modified version of the fisheries profit function. We consider our attempt in this direction a significant contribution to the literature.

Previous studies demonstrate that the dependency problem associated with computed efficiency scores violates the regression assumptions of independence between the error term and the discretionary variables. It is also established that as a result a number of estimation methods employed in the regression analysis are either invalid or inappropriate (Simar and Wilson, 2007; Barros and Assaf, 2009). Following the recent developments in the literature that address these estimation challenges (see Simar and Wilson, 2011) we have applied the truncated regression method with bootstrap in the investigation of the South Australian Rock Lobster Fishery. The uniqueness of this approach is that the regression equation is determined by the structure from which the DEA efficiency scores are obtained as well as ensuring consistent estimation using the maximum likelihood method. In addition, the bootstrap method is known to provide the only feasible means for inference. Furthermore, this method is relatively new in the fisheries context and, as far as we are aware, this is the first study to apply the method to the South Australian Rock Lobster Fishery.

The methods discussed in this Chapter have been applied to small sample cross-sectional data. Future work will extend the analysis to a balanced panel data to help elicit possible efficiency changes over time. Finally, using zone (regional) specific environmental characteristics (for example, distance to fishing grounds, crew travel time, tidal strength at different times of the fishing season, seasonal water temperatures) to help capture their significance in profit efficiency of any fisheries, including the South Australian Fishery, will be an interesting extension.
Chapter 6

Concluding Remarks

This thesis has addressed three main fisheries management issues: monitoring and enforcement; profit efficiency; and non-discretionary factors determining profit efficiency. These provide the necessary framework for the stock-profit link. Chapter 3 investigated whether strategic interaction between fishing firms and management in the presence of IUU has any effect on the fish stock. The objective was to provide a theoretical analysis of challenges in fisheries management that impact sustainability concerns in the industry. To conduct this investigation we used a game theoretic approach to consider the firm’s choice of legal and illegal effort to maximize profit in response to the fisheries manager’s choice of regulation, in the form of harvest quota, and enforcement as; fines, inspection probabilities, and group classification. The interaction was modeled as a two-person dynamic game which gave rise to a steady-state equilibrium. This equilibrium characterized the enforcement strategy of the manager in response to the firms’ compliance and violation behaviour. This also allowed consideration of the dynamic effect on fish stocks. The optimal enforcement strategy was found to involve less than perfect monitoring.

To effectively analyse the effect of firms’ effort choices on stock levels, it was important to understand why even firms that regularly comply may choose to violate
at one time or the other. In line with this we assumed rent-seeking behaviour as the main motivation for violation, and that any illegal effort increased catch levels above the allowable quota and consequently impacted the biomass negatively. We found that IUU activities require placing less value on the future of fisheries, that is, using a discount factor that heavily discounts the future of stocks and, consequently erodes any investment in the industry. In other words, failure to control IUU activities results in fishing future stocks in the current period so places less value on future stocks.

We also found that optimal compliance cannot be perfect, and that inspection has a lower bound. The consequence is that even though management would expect to observe perfect compliance from all firms, in equilibrium perfect compliance is not achievable. Achieving perfect compliance in equilibrium would require that the inspection of violating firms or the transition probability of moving firms between groups be reduced to zero. This thesis has shown that doing this is excessively costly, and therefore it is not optimal to do so. Furthermore, contrary to empirical suggestions that maximum penalties be increased considerably, results in this thesis indicate that punishment should have upper bound if it is to achieve the purpose for which it is intended. We demonstrated that marginal punishment exceeding marginal gains will only serve to increase illegal effort with attendant negative effect on fish stocks. This is to say that as punishment exceeds any additional benefits from illegal effort, illegal effort grows infinitely positive. We pointed out that this may well explain an earlier argument in the literature that firms making losses may continue to violate knowing that vessels and cheap labour can easily be replaced when caught and punished.

The application of game theoretic concepts to analyse illegal activities in fisheries, as shown in this thesis, is innovative. It provides insightful results that can guide
policy in the quest to address the IUU problem, and conserve and sustain fish stocks across time. We believe that this is one of the first applications of such an approach to understand the complex interactions between management and firms in the fishery industry. This chapter, in addition to addressing some of the management challenges identified in Chapter 2 of the thesis, also provided theoretical basis for the empirical investigation of the effect of biomass changes on profit efficiency examined in Chapters 4 and 5.

In Chapter 4 the sustainability question was pushed further by undertaking an empirical analysis to evaluate profit efficiency in the South Australian Rock Lobster Fishery. The importance of the rock lobster fishery to the state’s fishing industry makes the critical examination of its economic performance crucial to understanding the sustainability of the fishery. Poor profit performance coupled with persistent declines in stock levels, particularly the Northern Zone of the fishery, has raised concerns over the sustainability of the South Australian Rock Lobster Fishery. Using the Nerlovian method of efficiency evaluation, together with the Directional Distance Function concept, profit efficiency of the fishery was decomposed into technical and allocative efficiencies. This decomposition is useful because it provides more information that can better guide management and policy decision making. Previous analysis of the fishery’s economic performance, based on cost and revenue, indicates that the Southern Zone of the fishery is more profitable and therefore perceived to be more profit efficient compared to its Northern counterpart. In contrast to the existing perception about profit performance in the fisheries, profit efficiency in the Northern Zone of the fishery is found to be significantly higher, on average, than the South.

Profit inefficiency in the South Australian Rock Lobster Fishery, as a whole, can be largely attributed to allocative (managerial) inefficiency. In addition, major
challenges facing the fishery are identified to include significant drops in stock levels, decline in harvest values due to exchange rate shocks, and increases in effort coupled with significant falls in catch rate. The Nerlovian method, as shown here, has strong computational advantage and has been shown to possess unique potential for profit analysis in fisheries. The decomposition method applied in the thesis is another approach that fits well in efficiency analysis in the fisheries literature.

The main objectives of Chapter 5 were two-fold. The first was to provide a theoretical basis to justify the need to consider the importance of vessel capital when evaluating profit efficiency in fisheries. The second was to empirically identify factors beyond firms’ control which can significantly affect profit efficiency in fisheries. To achieve the first objective a modified version of the cost structure in a standard fisheries model was used to theoretically analyse the effect on profits and fish stocks. We did this by introducing a fixed input, as well as the usual variable input, into a conventional fisheries profit function, and carried out the analysis under both the short- and long-run. In an industry where fixed costs are considered non-malleable, the examination provides interesting theoretical insights into the significance of such costs in profit analysis in both the short- and long-runs.

The theoretical analysis suggests that although the effect of vessel size can be ambiguous, if effort is closer to optimal vessel size profits will rise. However, profits will fall if having a larger vessel exacerbates the sub-optimality of effort use. The theoretical analysis further showed that as long as the cost associated with sub-optimal use of vessel size remains positive but less than fixed costs the equilibrium stock level is negatively affected. The empirical analysis was conducted using a truncated regression with bootstrap on profit efficiency measures from the South Australian Rock Lobster Fishery. We found, as with the larger fisheries literature, that greater biomass will increase profits. Specifically, we found that increasing
biomass has a positive effect on profits, but at a decreasing rate which is consistent with the predictions from our theoretical examination.

We also found empirical evidence to suggest that unfavourable exchange rate position of the rock lobster fishery with its major trading partners may explain some of the allocative (managerial) challenges that negatively impact profit efficiency in the fishery. This negative price effect in the empirical results can be attributed to a short-run negative effect resulting from unfavourable exchange rate shocks in the periods considered for the study. This observation supports our theoretical findings that increases in prices are good for profits in the short-run.

Empirically we also examined the impact of having an ITQ management system and found that it had a positive impact on profit efficiency. The ITQ effect is found to generally agree with existing literature on the benefits of the ITQ introduction in fisheries.

The methods applied in Chapter 5 are a unique approach that determines the regression equation by the structure from which the DEA efficiency scores are obtained, addresses estimation problems in the literature by ensuring consistent estimation, and is also relatively new in the fisheries context. In addition, the bootstrap method is known to provide the only feasible means for inference. These methods have been applied to small sample cross-sectional data in this thesis.

It needs to be mentioned that the thesis had some limitations, including data challenges. Data availability in fisheries poses an ongoing challenge. The small and unequal sample sizes, for example, makes comparisons between the two fisheries investigated difficult, especially where the method of estimation is sensitive to small sample sizes, as in the case of the directional distance function. While the methods used in this thesis were chosen to alleviate data problems, a full understanding
of profit efficiency in any fisheries analysis would benefit from a large number of observations and finer details regarding input and output quantities and values.

Further work will use the game theoretic interactive method to find a plausible solution to IUU challenges in internationally shared fisheries. The assumption that the probability of inspection is not affected by the incidence of violation, used in the model developed in Chapter 3, will also be investigated in future work. To further illuminate the true potential of the methods used in Chapter 4 in fisheries, future work will focus on applying the techniques in other fisheries. Finally, the truncated regression analysis will be extended to a balanced panel data to help elicit possible efficiency changes occurring over time.
Bibliography


Appendix A

Additional Materials and Proofs Related to Chapter 3

Appendix A.1

The expected profit of a group 1 firm complying at all times, can be expressed as

\[ E^{\infty}[\pi_{1c}] = \pi_{1c} + \beta \pi_{1c} + \beta^2 \pi_{1c} + \beta^3 \pi_{1c} + \ldots = \pi_{1c} + \beta \left( \pi_{1c} + \beta \pi_{1c} + \beta^2 \pi_{1c} + \ldots \right) = \pi_{1c} + \sum_{t=1}^{\infty} \beta^t \pi_{1c}. \]

By the stationarity and infinite time horizon assumption, the expected profit of a group 1 firm complying at all times, \( E^{\infty}[\pi_{1c}] \), can be expressed

\[ E^{\infty}[\pi_{1c}] = \pi_{1c} + \beta \left( \pi_{1c} + \beta \pi_{1c} + \beta^2 \pi_{1c} + \ldots \right) = \pi_{1c} + \beta E^{\infty}[\pi_{1c}] \]

For a type 2 firm complying all the time, let the expected profit be given as

\[ E^{\infty}[\pi_{2c}] = \pi_{2c} + \beta \left[ \mu_2 \eta \pi_{1c} + (1 - \mu_2 \eta) \pi_{2c} \right] + \beta^2 \left[ \mu_2 \eta \pi_{1c} + (1 - \mu_2 \eta) \pi_{2c} \right] + \ldots = \pi_{2c} + \sum_{t=1}^{\infty} \beta^t (\mu_2 \eta \pi_{1c}) + \sum_{t=1}^{\infty} \beta^t (1 - \mu_2 \eta) \pi_{2c} = \pi_{2c} + \mu_2 \eta \sum_{t=1}^{\infty} \beta^t \pi_{1c} + (1 - \mu_2 \eta) \sum_{t=1}^{\infty} \beta^t \pi_{2c} \]
Then by the stationarity and infinite time horizon assumption, the expected profit of a group 2 firm complying at all times, \( E^{00}[\pi_{2c}] \), can be expressed as

\[
E^{00}[\pi_{2c}] = \pi_{2c} + \mu_2 \eta \beta \left[ \sum_{t=0}^{\infty} \beta^t \pi_{1c} \right] + (1 - \mu_2 \eta) \beta \left[ \sum_{t=0}^{\infty} \beta^t \pi_{2c} \right]
\]

Analogically the cases of violation for group 1 and group 2 firms are derived and expressed in Table 3.4.

**Appendix A.2**

Solving the equations under Section 3.2.3.

In order to obtain the expected profits of the four strategies each firm adopts, the equations in Table 3.4 are solved simultaneously in the following manner.

[A]. Solving for expected profits under strategy \( s_{00} \), i.e. comply in both groups \( G_1 \) and \( G_2 \)

Let \( E^{00}[\pi_{1c}] : \ E^{00}[\pi_{1c}] = \pi_{1c} + \beta E^{00}[\pi_{1c}] \)

This gives \( E^{00}[\pi_{1c}](1 - \beta) = \pi_{1c} \),

yielding

\[
E[\pi_{1c}] = \frac{\pi_{1c}}{1 - \beta} \quad (A.1)
\]

Next, letting, \( E^{00}[\pi_{2c}] : \ E[\pi_{2c}] = \pi_{2c} + \beta \mu_2 \eta E[\pi_{1c}] + \beta (1 - \mu_2 \eta) E[\pi_{2c}] \),

yields

\[
E[\pi_{2c}][1 - \beta(1 - \mu_2 \eta)] = \pi_{2c} + \beta \mu_2 \eta E[\pi_{1c}]
\]

Then substituting for \( E[\pi_{1c}] \) from (A.1)

we obtain
\[
E[\pi_{2c}][1 - \beta(1 - \mu_2\eta)] = \pi_{2c} + \beta\mu_2\eta\left(\frac{\pi_c}{1 - \beta}\right)
\]

and

\[
E[\pi_{2c}] = \frac{(1 - \beta)\pi_c + \beta\mu_2\eta\pi_c}{(1 - \beta)(1 - \beta(1 - \mu_2\eta))}.
\]

Rearranging the numerator of the above equation and canceling terms, the following result is obtained

\[
E[\pi_{2c}] = \frac{\pi_c}{1 - \beta}.
\] (A.2)

[B]. Solving for expected profits under strategy \(s_{01}\), i.e. comply in group \(G_1\) and violate in \(G_2\)

Letting \(E^{01}[\pi_{1c}] : E[\pi_{1c}] = \pi_c + \beta E[\pi_{1c}]\)

and re-arranging yields

\[
E[\pi_{1c}] = \frac{\pi_c}{1 - \beta}.
\] (A.3)

From \(E^{01}[\pi_{2c}] : E[\pi_{2c}] = \pi_{2v} - \mu_2F + \beta E[\pi_{2v}]\)

we obtain

\[
E[\pi_{2v}] = \frac{\pi_{2v} - \mu_2F}{1 - \beta}.
\] (A.4)

[C]. Solving for expected profits under strategy \(s_{10}\), i.e. a firm violating in group \(G_1\) and complying in \(G_2\), yield the following respective results for \(G_1\) and \(G_2\) firms
As before, we first let, $E^{10}[\pi_{1v}] : E[\pi_{1v}] = \pi_{1v} - \mu_1 F + \mu_1 \beta E[\pi_{2c}] + \beta(1 - \mu_1)E[\pi_{1v}]$,

from which we obtain;

$$E[\pi_{1v}][1 - \beta(1 - \mu_1)] = \pi_{1v} - \mu_1 F + \mu_1 \beta E[\pi_{2c}], \quad (A.5)$$

and therefore

$$E[\pi_{1v}] = \frac{\pi_{1v} - \mu_1 F + \mu_1 \beta E[\pi_{2c}]}{1 - \beta(1 - \mu_1)}, \quad (A.6)$$

after the necessary re-arrangements.

Next, for $E^{10}[\pi_{2c}] : E[\pi_{2c}] = \pi_c + \beta \mu_2 \eta E[\pi_{1v}] + \beta(1 - \mu_2 \eta)E[\pi_{2c}]$

we obtain

$$E[\pi_{2c}][1 - \beta(1 - \mu_2 \eta)] = \pi_c + \beta \mu_2 \eta E[\pi_{1v}]$$

Then plugging in $E[\pi_{1v}]$ from (A.6) yields

$$E[\pi_{2c}][1 - \beta(1 - \mu_2 \eta)] = \pi_c + \beta \mu_2 \eta \left( \frac{\pi_{1v} - \mu_1 F + \mu_1 \beta E[\pi_{2c}]}{1 - \beta(1 - \mu_1)} \right).$$

After the necessary expansion of the above equation the following is obtained

$$E[\pi_{2c}][1 - \beta(1 - \mu_2 \eta)(1 - \beta(1 - \mu_1))] = \pi_c[1 - \beta(1 - \mu_1)] + \beta \mu_2 \eta(\pi_{1v} - \mu_1 F) + \beta^2 \mu_1 \mu_2 \eta E[\pi_{2c}]$$

and which results in

$$E[\pi_{2c}][1 - \beta(1 - \mu_2 \eta)(1 - \beta(1 - \mu_1)) - \beta^2 \mu_1 \mu_2 \eta] = \pi_c[1 - \beta(1 - \mu_1)] + \beta \mu_2 \eta(\pi_{1v} - \mu_1 F).$$

To obtain the required expression for $E[\pi_{2c}]$, expected profit when complying in group 2, we do the following. We let the L.H.S be defined as $A$ and the R.H.S as $B$, such that $A = B$.

Then simplifying $A$

$$A = E[\pi_{2c}][1 - \beta(1 - \mu_1) - \beta(1 - \mu_2 \eta) + \beta^2(1 - \mu_1)(1 - \mu_2 \eta) - \beta^2 \mu_1 \mu_2 \eta]$$

$$= E[\pi_{2c}][1 - \beta(1 - \mu_1) - \beta(1 - \mu_2 \eta) + \beta^2(1 - \mu_1 - \mu_2 \eta + \mu_1 \mu_2 \eta) - \beta^2 \mu_1 \mu_2 \eta]$$

$$= E[\pi_{2c}][1 - \beta(1 - \mu_1) - \beta(1 - \mu_2 \eta) + \beta^2(1 - \mu_1 - \mu_2 \eta) + \beta \mu_1 \mu_2 \eta - \beta^2 \mu_1 \mu_2 \eta]$$

$$= E[\pi_{2c}][1 - \beta(1 - \mu_1) - \beta + \beta \mu_2 \eta + (1 - \mu_1) - \beta^2 \mu_2 \eta]$$

$$= E[\pi_{2c}][1 - \beta(1 - \mu_1)(1 - \beta) - \beta + \beta \mu_2 \eta(1 - \beta)]$$

$$= E[\pi_{2c}](1 - \beta)[1 - \beta(1 - \mu_1) + \beta \mu_2 \eta] = E_{2c}(1 - \beta)[1 - \beta(1 - \mu_1 - \mu_2 \eta)].$$

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Then equating $A = B$, yields the following expression

$$E[\pi_v](1 - \beta)[1 - \beta(1 - \mu_1 - \mu_2\eta)] = \pi_c[1 - \beta(1 - \mu_1)] + \beta\mu_2\eta(\pi_{1v} - \mu_1F)$$

which is re-arranged to give the following expression for $E[\pi_{2c}]$

$$E[\pi_{2c}] = \frac{\pi_c[1 - \beta(1 - \mu_1)] + \beta\mu_2\eta(\pi_{1v} - \mu_1F)}{(1 - \beta)[1 - \beta(1 - \mu_1 - \mu_2\eta)]}. \tag{A.7}$$

Then plugging (A.7) back into (A.6) above, results in

$$E[\pi_{1v}] = \frac{\pi_{1v} - \mu_1F + \mu_1\beta\left(\frac{\pi_c[1 - \beta(1 - \mu_1)] + \beta\mu_2\eta(\pi_{1v} - \mu_1F)}{(1 - \beta)[1 - \beta(1 - \mu_1 - \mu_2\eta)]}\right)}{[1 - \beta(1 - \mu_1)]}.$$

We then simplify the numerator of the above expression as follows.

We let

$$\Delta = \frac{(\pi_{1v} - \mu_1F)(1 - \beta)[1 - \beta(1 - \mu_1 - \mu_2\eta)] + \beta\mu_1\pi_c[1 - \beta(1 - \mu_1)] + \beta^2\mu_1\mu_2\eta(\pi_{1v} - \mu_1F)}{(1 - \beta)[1 - \beta(1 - \mu_1 - \mu_2\eta)]}$$

$$= \frac{(\pi_{1v} - \mu_1F)(1 - \beta)[1 - \beta(1 - \mu_1)] + (\pi_{1v} - \mu_1F)(1 - \beta)\beta\mu_2\eta + \beta\mu_1\pi_c[1 - \beta(1 - \mu_1)] + \beta^2\mu_1\mu_2\eta(\pi_{1v} - \mu_1F)}{(1 - \beta)[1 - \beta(1 - \mu_1 - \mu_2\eta)]}$$

$$= \frac{[1 - \beta(1 - \mu_1)][(1 - \beta)(\pi_{1v} - \mu_1F) + \beta\mu_2\eta(\pi_{1v} - \mu_1F) + \beta\mu_1\pi_c]}{(1 - \beta)[1 - \beta(1 - \mu_1 - \mu_2\eta)]}.$$

Next, is to put the numerator and denominator of $E[\pi_{1v}]$ together to obtain the following expression

$$E[\pi_{1v}] = \frac{[1 - \beta(1 - \mu_1)][(\pi_{1v} - \mu_1F)(1 - \beta) + \beta\mu_2\eta(\pi_{1v} - \mu_1F) + \beta\mu_1\pi_c]}{(1 - \beta)[1 - \beta(1 - \mu_1 - \mu_2\eta)]}. \tag{A.8}$$

We then cancel out terms to obtain the desired expression in $E[\pi_{1v}]$ and $E[\pi_{2c}]$, as

$$E[\pi_{1v}] = \frac{\beta\mu_1\pi_c + (\pi_{1v} - \mu_1F)[1 - \beta(1 - \eta_2\eta)]}{(1 - \beta)[1 - \beta(1 - \mu_1 - \mu_2\eta)]}$$

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and;

\[ E[\pi_{1v}] = \frac{\pi_v[1 - \beta(1 - \mu_1)] + \beta \mu_2 \eta(\pi_{1v} - \mu_1 F)}{(1 - \beta)[1 - \beta(1 - \mu_1 - \mu_2 \eta)]} \]  

(A.9)

[D]. Solving for expected profits under strategy \( s_{11} \), that is, violating in both states \( G_1 \) and \( G_2 \)

As before, we let \( E^{11}[\pi_{1v}] : E[\pi_{1v}] = \pi_{1v} - \mu_1 F + \mu_1 \beta E_{2v} + \beta (1 - \mu_1) E[\pi_{1v}] \).

We then re-arrange the above to obtain equation (A.10), as

\[ E[\pi_{1v}] = \frac{\pi_{1v} - \mu_1 F + \mu_1 \beta E[\pi_{2v}]}{1 - \beta(1 - \mu_1)} \]  

(A.10)

Similarly, letting, \( E^{11}[\pi_{2v}] : E[\pi_{2v}] = \pi_{2v} - \mu_2 F + \beta E[\pi_{2v}] \), and re-arranging yields

\[ E[\pi_{2v}] = \frac{\pi_{2v} - \mu_2 F}{1 - \beta} \]  

(A.11)

To obtain the desired expression in \( E[\pi_{1v}] \), we substitute (A.11) back into (A.10) above and re-arrange to get equation (A.12) as follows

\[ E[\pi_{1v}] = \frac{\pi_{2v} - \mu_1 F + \beta \left( \frac{\pi_{2v} - \mu_2 F}{1 - \beta} \right)}{1 - \beta(1 - \mu_1)} = \frac{(1 - \beta)[\pi_{1v} - \mu_1 F] + \mu_1 \beta(\pi_{2v} - \mu_2 F)}{(1 - \beta)(1 - \beta(1 - \mu_1))} \]

and hence

\[ E[\pi_{1v}] = \frac{(1 - \beta)[\pi_{1v} - \mu_1 F] + \mu_1 \beta(\pi_{2v} - \mu_2 F)}{(1 - \beta)(1 - \beta(1 - \mu_1))} \]  

(A.12)

Thus, solving for expected profits under strategy \( s_{11} \), that is, violating in both groups \( G_1 \) and \( G_2 \), produce the following results for groups 1 and 2 firms violating as

\[ E[\pi_{1v}] = \frac{(1 - \beta)[\pi_{1v} - \mu_1 F] + \mu_1 \beta(\pi_{2v} - \mu_2 F)}{(1 - \beta)(1 - \beta(1 - \mu_1))} \]  

(A.13)

and

\[ E[\pi_{2v}] = \frac{\pi_{2v} - \mu_2 F}{1 - \beta}. \]  

(A.14)
Proof of Lemmas

Lemma 1

1. Starting with the condition \( \pi_c > \pi_{2v} - \mu_2 F \)

   From Equations (A.1 and A.4), \( \frac{\pi_c}{1-\beta} = \frac{\pi_{2v} - \mu_2 F}{1-\beta} \) iff \( \pi_c = \pi_{2v} - \mu_2 F \) \( \forall \beta \neq 1 \). But the condition \( \pi_c > \pi_{2v} - \mu_2 F \) \( \Rightarrow \frac{\pi_c}{1-\beta} > \frac{\pi_{2v} - \mu_2 F}{1-\beta} \), \( \forall \beta \neq 1 \). This implies \( S_{00} > S_{01} \), from the profit maximizing assumption.

2. Condition \( \pi_c < \pi_{2v} - \mu_2 F \)

   From Equation (A.12), \( \frac{(1-\beta)[\pi_{1v} - \mu_1 F] + \mu_1 \beta(\pi_{2v} - \mu_2 F)}{(1-\beta)[1-\beta(1-\mu_1)]} > \frac{(1-\beta)[\pi_{1v} - \mu_1 F] + \mu_1 \beta \pi_c}{(1-\beta)[1-\beta(1-\mu_1)]} \), iff \( \pi_{2v} - \mu_2 F > \pi_c \). Rearranging this relation yields
   \[
   \frac{\pi_{2v} - \mu_2 F}{1-\beta} > \frac{\pi_c}{1-\beta}, \quad \forall \beta \neq 1.
   \]

   Again, from the profit maximizing assumption this implies \( S_{11} > S_{01} \). Hence (1) and (2) satisfy Lemma 1. □

Lemma 2

From Equation (A.7) when \( \pi_c = \pi_{1v} - \mu_1 F \) the following is observed: \( \frac{\pi_c[1-\beta(1-\mu_1)] + \beta \mu_2 \eta(\pi_{1v} - \mu_1 F)}{(1-\beta)[1-\beta(1-\mu_1 - \mu_2 \eta)]} = \frac{\pi_c[1-\beta(1-\mu_1 - \mu_2 \eta)]}{(1-\beta)[1-\beta(1-\mu_1 - \mu_2 \eta)]} \), yielding \( \frac{\pi_c}{1-\beta} = E^{00} \). Equation (A.1) implies \( E^{00} = \frac{\pi_c}{1-\beta} \), giving \( E^{00} = E^{10} \). Equation (A.14) implies \( E^{11} = \frac{\pi_{2v} - \mu_2 F}{1-\beta} \). But the condition \( \pi_c > \pi_{2v} - \mu_2 F \) shows that \( \frac{\pi_c}{1-\beta} > \frac{\pi_{2v} - \mu_2 F}{1-\beta} \), \( \forall \beta \neq 1 \). Hence \( E^{00} = E^{10} > E^{11} \), and therefore \( S_{00} = S_{10} > S_{11} \). From the profit maximizing assumption \( S_{00} = S_{10} \) satisfies Lemma 2. □
Appendix A.3

Solving the optimization problem with respect to $\mu_1, \mu_2, F, \eta, \gamma,$ and $\varphi$. We first let the leverage, $L$, be expressed as

$$L = \frac{\mu_1 \mu_2 (1 + \eta)}{\mu_1 + \mu_2 \eta} + \gamma \left[ \pi_2 - \mu_2 F + \frac{\beta \mu_2 \eta \pi_2 - \pi_1 \mu + \mu_1 F - \mu_2 F}{1 - \beta (1 - \mu_1)} - \pi_c \right] + \varphi \left[ \Omega - \frac{\mu_1}{\mu_1 + \mu_2 \eta} \right]$$

We then take the first order condition (FOC) with respect to each of the parameters above.

Starting with $\mu_1$.

Let

$$\frac{\partial L}{\partial \mu_1} = \frac{\mu_2 (1 + \eta) (\mu_1 + \mu_2 \eta)}{(\mu_1 + \mu_2 \eta)^2} + \frac{\gamma \beta \mu_2 \eta \pi_2 - \mu_1 F}{1 - \beta (1 - \mu_1)} - \frac{\gamma \beta \mu_2 \eta F [1 - \beta (1 - \mu_1)]}{1 - \beta (1 - \mu_1)^2} = 0.$$

Re-arranging the above, we solve for $\varphi$ as follows:

$$\frac{\mu_2 (1 + \eta) [\mu_1 + \mu_2 \eta - \mu_1]}{(\mu_1 + \mu_2 \eta)^2} - \frac{\varphi [\mu_1 + \mu_2 \eta - \mu_1]}{(\mu_1 + \mu_2 \eta)^2} + \frac{\gamma \beta \mu_2 \eta F [1 - \beta (1 - \mu_1)] - \gamma \mu_1 \mu_2 \beta \eta F}{1 - \beta (1 - \mu_1)^2} = 0$$

giving

$$\frac{\mu_2 (1 + \eta) - \varphi}{(\mu_1 + \mu_2 \eta)^2} + \frac{\gamma \beta F (1 - \beta)}{1 - \beta (1 - \mu_1)^2} = 0$$

and therefore

$$\varphi = \mu_2 (1 + \eta) + \frac{\gamma \beta F (1 - \beta) (\mu_1 + \mu_2 \eta)^2}{1 - \beta (1 - \mu_1)^2}.$$  \hspace{1cm} (A.15)

Next, is the FOC with respect to $\mu_2$.

Let

$$\frac{\partial L}{\partial \mu_2} = \frac{\mu_1 (1 + \eta) (\mu_1 + \mu_2 \eta) - \mu_1 \mu_2 (1 + \eta) \eta}{(\mu_1 + \mu_2 \eta)^2} - \gamma F - \frac{2 \gamma \beta \mu_2 \eta F [1 - \beta (1 - \mu_1)]}{1 - \beta (1 - \mu_1)^2} \left[ - \frac{\varphi \mu_1 \eta}{(\mu_1 + \mu_2 \eta)^2} \right] = 0.$$

Re-arranging the above we obtain the expression in (A.16) as:

$$\frac{\mu_1 (1 + \eta) [\mu_1 + \mu_2 \eta - \mu_2 \eta] + \varphi \mu_1 \eta}{(\mu_1 + \mu_2 \eta)^2} - \gamma F - \frac{2 \gamma \beta \mu_2 \eta F}{1 - \beta (1 - \mu_1)} = 0.$$
and therefore

\[
\frac{ \mu_1[\mu_1(1 + \eta) + \varphi \eta]}{(\mu_1 + \mu_2 \eta)^2} = \frac{\gamma F [1 - \beta(1 - \mu_1) + 2\beta \mu_2 \eta]}{1 - \beta(1 - \mu_1)} \tag{A.16}
\]

Next, is the FOC with respect to \( F \).

Let

\[
\frac{\partial L}{\partial F} = -\gamma \mu_2 + \frac{\gamma \beta \mu_2 \eta (\mu_2 - \mu_1) [1 - \beta(1 - \mu_1)]}{1 - \beta(1 - \mu_1)} = 0.
\]

By re-arrangement, we solve for \( \mu_1 \) as follows

Let

\[
\frac{\gamma \beta \mu_2 \eta (\mu_2 - \mu_1) - \gamma \mu_2 [1 - \beta(1 - \mu_1)]}{1 - \beta(1 - \mu_1)} = 0
\]

and;

\[
\mu_1 \beta (\eta - 1) = \beta (\eta \mu_2 - 1) + 1
\]

Thus, obtaining \( \mu_1 \) as

\[
\mu_1 = \frac{\beta (\eta \mu_2 - 1) + 1}{\beta (\eta - 1)} \tag{A.17}
\]

The FOC with respect to \( \eta \) is next.

Let

\[
\frac{\partial L}{\partial \eta} = \frac{\mu_1 \mu_2 (\mu_1 + \mu_2 \eta) - \mu_1 \mu_2 (1 + \eta) \mu_2}{(\mu_1 + \mu_2 \eta)^2} + \frac{\gamma \beta \mu_2 [\pi_2 - \pi_1 + \mu_1 F - \mu_2 F]}{1 - \beta(1 - \mu_1)} - \left[ \frac{\varphi \mu_1 \mu_2}{(\mu_1 + \mu_2 \eta)^2} \right] = 0
\]

\[
= \frac{\mu_1 \mu_2 (\mu_1 + \mu_2 \eta) - \mu_1 \mu_2 (1 + \eta) \mu_2 + \varphi \mu_1 \mu_2}{(\mu_1 + \mu_2 \eta)^2} + \frac{\gamma \beta \mu_2 [\pi_2 - \pi_1 + \mu_1 F - \mu_2 F]}{1 - \beta(1 - \mu_1)} = 0.
\]

We re-organise the above to obtain the expression (A.18) below.

\[
\frac{\mu_1 (\mu_1 - \mu_2 + \varphi)}{(\mu_1 + \mu_2 \eta)^2} = -\frac{\gamma \beta \mu_2 [\pi_2 - \pi_1 + \mu_1 F - \mu_2 F]}{1 - \beta(1 - \mu_1)} \tag{A.18}
\]

Next, is the FOC with respect to \( \gamma \)

Let
\[
\frac{\partial L}{\partial \gamma} = \pi_2 - \mu_2 F + \frac{\beta \mu_2 \eta [\pi_2 - \pi_1 + \mu_1 F - \mu_2 F]}{1 - \beta (1 - \mu_1)} - \pi_c = 0
\]

Similarly, after the necessary re-arrangements, we solve for \(\pi_c\) as
\[
\pi_c = \pi_2 - \mu_2 F + \frac{\beta \mu_2 \eta [\pi_2 - \pi_1 + \mu_1 F - \mu_2 F]}{1 - \beta (1 - \mu_1)}.
\] (A.19)

Finally, we do the same with respect to \(\varphi\), and solve for \(\Omega\) as follows
\[
\frac{\partial L}{\partial \varphi} = \Omega - \frac{\mu_1}{\mu_1 + \mu_2 \eta} = 0
\]

which yields
\[
\Omega = \frac{\mu_1}{\mu_1 + \mu_2 \eta}
\] (A.20)
Appendix A.4

The objective here is to solve for marginal revenue (\(MR\)) and marginal cost (\(MC\)), given legal (\(E^L\)) and illegal (\(E^{IL}\)) efforts, using the revenue and cost functions.

\[
TR_{10} = \frac{pqK}{A} \left[ (\beta + Q) \left( E^L - \frac{q}{r}E^{2L} + E^{IL}E^L \right) + Q \left( E^{IL} - \frac{q}{r}[E^L E^{IL} + E^{2IL}] \right) \right]
\]

\[
TC_{10} = \frac{1}{A} \left[ c \left( (\beta + Q)E^L + QE^{IL} \right) + Q\mu_1fqK \left( E^{IL} - \frac{q}{r}[E^L E^{IL} + E^{2IL}] \right) \right]
\]

After the necessary expansion of both equations, the following first order conditions are determined

1. We first take the FOC with respect to \(E^L\), giving us the \(MR\) and \(MC\) with respect to \(E^L\) as, respectively

\[
\frac{\partial TR_{10}}{\partial E^L} = \frac{pqK}{A} \left[ (\beta + Q) \left( 1 - \frac{q}{r}[2E^L + E^{IL}] \right) - \frac{q}{r}QE^{IL} \right]
\]

and

\[
\frac{\partial TC_{10}}{\partial E^L} = \frac{1}{A} \left[ c(\beta + Q) - \frac{q^2}{r}Q\mu_1fKE^{IL} \right].
\]

For maximum economic yield (\(MEY\)), given \((E^L, E^{IL})\), implies that \(\frac{\partial TR_{10}}{\partial E^L} = \frac{\partial TC_{10}}{\partial E^L}\), which is equivalent to \(MR_{E^L} = MC_{E^L}\).

Recall that \(A = (1 - \beta)[1 - \beta(1 - \mu_1 - \mu_2\eta)]\), and \(Q = [1 - \beta(1 - \mu_1\eta)]\)

Thus after equating and re-arranging the above FOCs, the \(MEY\) legal effort level chosen by firms when violating under strategy \(s_{10}\) is given as

\[
E^L_{MEY/10} = \frac{r}{2q} \left( 1 - \frac{c}{pqK} \right) - \frac{1}{2p} \left[ p + \frac{Q(p - \mu_1f)}{(\beta + Q)} \right] E^{IL}_{MEY/10}.
\]

2. As before we find \(MR\) and \(MC\) with respect to \(E^{IL}\), as follows
Let;
\[
\frac{\partial TR_{10}}{\partial E^{IL}} = \frac{pqK}{A} \left[ Q(1 - 2\frac{q}{r}E^{IL}) - \frac{q}{r}(\beta + 2Q) \right]
\]
and
\[
\frac{\partial TC_{10}}{\partial E^{IL}} = \frac{Q}{A} \left[ c + \mu_1 f qK \left( 1 - \frac{q}{r}|E^L + 2E^{IL}| \right) \right].
\]
Again, for maximum economic yield (MEY), given \((E^L, E^{IL})\), implies that \(\frac{\partial TR_{10}}{\partial E^{IL}} = \frac{\partial TC_{10}}{\partial E^{IL}}\), which is equivalent to \(MR_{E^{IL}} = MC_{E^{IL}}\).

This relation gives the following MEY illegal effort level chosen by firms when violating under strategy \(S_{10}\)
\[
E_{MEY/10}^{IL} = \frac{r}{2q} \left( 1 - \frac{c}{qK(p - \mu_1 f)} \right) - \frac{1}{2} \left[ 1 + \frac{(\beta + Q)p}{Q(p - \mu_1 f)} \right] E_{MEY/10}^L.
\]
Appendix A.5

Proof 1.

No illegal fishing benchmark.

Let the Hamiltonian be expressed as

\[ H = e^{-\delta t} \left\{ (pqB_t - c)E_t + \lambda_t \left[ rB_t \left( 1 - \frac{B_t}{K} \right) - qB_tE_t \right] \right\} \]

and the necessary condition with respect to effort, \( E_t \), be given as

\[(pqB_t - c) - \lambda_t qB_t = 0\]

Then re-arranging and solving for \( \lambda_t \), gives

\[ \lambda_t = \frac{pqB_t - c}{qB_t}. \]

which can also be written in the form:

\[ \lambda_t = p - \frac{c}{qB_t}. \]

The necessary condition with respect to biomass, \( B_t \), yields

\[ pqE_t + \lambda_t r \left( 1 - \frac{2B_t}{K} \right) - \lambda_t qE_t = -\dot{\lambda}_t + \delta \lambda_t \quad \text{(A.21)} \]

Finally the necessary condition with respect to \( \lambda_t \), results in

\[ E_t = \frac{r}{q} \left( 1 - \frac{B_t}{K} \right) \]

Sustainable steady-state requires that \( f(B, E) = qB^*E^* \), and \( \dot{B}_t = 0 = \dot{\lambda}_t \).

This implies

\[ E^* = \frac{r}{q} \left( 1 - \frac{B^*}{K} \right). \]
And from the steady-state conditions, Equation (21) becomes

$$\delta \lambda^\ast = pqE^\ast + \lambda^\ast r \left( 1 - \frac{2B^\ast}{K} \right) - \lambda^\ast qE^\ast$$

and

$$\lambda^\ast = \frac{pqB^\ast - c}{qB^\ast} = p - \frac{c}{qB^\ast}.$$  

Then substituting for $\lambda^\ast$ and solving for $\delta$ as follows gives the modified golden rule

Let

$$\delta \frac{pqB^\ast - c}{qB^\ast} = pq \left[ \frac{r}{q} \left( 1 - \frac{B^\ast}{K} \right) \right] + \left( p - \frac{c}{qB^\ast} \right) \left[ r \left( 1 - \frac{2B^\ast}{K} \right) - q \cdot \frac{r}{q} \left( 1 - \frac{B^\ast}{K} \right) \right]$$

After the necessary re-arrangements we get

$$\delta \frac{pqB^\ast - c}{qB^\ast} = \frac{pqB^\ast - c}{qB^\ast} \cdot r \left( 1 - \frac{2B^\ast}{K} \right) + \frac{c}{qB^\ast} \cdot r \left( 1 - \frac{B^\ast}{K} \right)$$

which finally gives the required expression for $\delta$ as

$$\delta = r \left( 1 - \frac{2B^\ast}{K} \right) + r \left( 1 - \frac{B^\ast}{K} \right) \frac{c}{pqB^\ast - c}. \square$$

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Proof 2

The case of IUU

From the assumption that firms conducting illegal activities employ illegal effort in addition to legal effort, we express the Hamiltonian as

$$H = e^{-\delta t} \left\{ (pqB_t - c)e_t^T - \mu_1 f q B_t (e_t^T - e_t^L) + \lambda_t \left[ rB_t \left( 1 - \frac{B_t}{K} \right) - qB_t e_t^T - (n - 1)qB_te_{jt}^T \right] \right\}.$$  

Recall that $e_t^T = e_t^L + e_t^{IL}$, which is equivalent to saying $e_t^{IL} = e_t^T - e_t^L$.

Then the necessary condition with respect to total effort of firm $i$ at time $t$, $e_{it}^T$, after re-arrangements, yields the following expression in $\lambda_t$

$$\lambda_t = \frac{qB_t(p - \mu_1 f) - c}{qB_t}.$$  

Then the necessary with respect to biomass, $B_t$, results in

$$p q e_{it}^T - \mu_1 f q (e_t^T - e_t^L) + \lambda_t \left\{ r \left( 1 - \frac{2B_t}{K} \right) - q e_{it}^T - (n - 1)q e_{jt}^T \right\} = -\dot{\lambda}_t + \delta \lambda_t.$$  

We assume symmetry about illegal effort choice, that is, all firms employing illegal effort are identical, thus $e_{it} = e_{jt} \equiv e_{it}$. Therefore, the necessary condition with respect to $\lambda_t$ gives, yields

$$e_{it}^T = r \frac{nq}{nq} \left( 1 - \frac{B_t}{K} \right).$$  

This gives the effort level at any time, $t$. Using the same symmetric assumption as above, let the steady-state effort be expressed as

$$\bar{e}^T = r \frac{nq}{nq} \left( 1 - \frac{B}{K} \right).$$  

Hence in steady-state we obtain the following the expression

$$p q \bar{e}^T - \mu_1 f q (\bar{e}^T - \bar{e}^L) + \tilde{\lambda} \left\{ r \left( 1 - \frac{2B}{K} \right) - q \bar{e}^T - (n - 1)q \bar{e}^T \right\} = \delta \bar{\lambda}.$$
After the necessary algebraic re-arrangements, and solving for $\delta$, we obtain the required $MGR$ as

$$\delta = r \left(1 - \frac{2B}{K}\right) - \frac{r}{n} \left(1 - \frac{B}{K}\right) \frac{q(n - 1)(p - \mu_1 f)B - nc}{qB(p - \mu_1 f) - c} + \frac{q^2 B \mu_1 f e^{1L}}{qB(p - \mu_1 f) - c}. \qed$$
Appendix B

Additional Materials Related to Chapter 4

Appendix B.1
Table B.1: Results of Welch two sample t-test

<table>
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<tr>
<td></td>
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<td>Mean</td>
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<tr>
<td>1997 - 98</td>
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<td>Southern Zone</td>
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<td></td>
<td>CI (95%)</td>
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<td>(-0.0852, 0.0831)</td>
<td>(-0.0754, 0.0569)</td>
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<td>Southern Zone</td>
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<td></td>
<td>t</td>
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<td>p-value</td>
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<td>0.2545</td>
<td>0.1930</td>
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<td>(-0.0315, 0.1162)</td>
<td>(-0.1019, 0.0211)</td>
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<td>2004 - 2005</td>
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<td>0.6591</td>
<td>0.2240</td>
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<td>CI (95%)</td>
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<td>(-0.0965, 0.0618)</td>
<td>(-0.1193, 0.0290)</td>
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<td>2007 - 08</td>
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<td>(-0.1014, 0.0350)</td>
<td>(-0.0859, 0.0623)</td>
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*NB: Values in parenthesis are the 95% confidence interval.*
Appendix B.2

Table B.2: Average values of non-discretionary variables

<table>
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<tr>
<th>Period</th>
<th>Zone</th>
<th>Boat age</th>
<th>Boat length</th>
<th>Engine age</th>
<th>Electrical Equip. age</th>
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<td>6.21</td>
<td>4.00</td>
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<td>SZ</td>
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<td>11.94</td>
<td>7.02</td>
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<td>10.24</td>
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<tr>
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<td>SZ</td>
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<td>11.89</td>
<td>4.28</td>
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<tr>
<td>2004/05</td>
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<td>19.50</td>
<td>10.19</td>
<td>10.19</td>
<td>5.95</td>
</tr>
<tr>
<td></td>
<td>SZ</td>
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<td>11.77</td>
<td>5.73</td>
<td>6.00</td>
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<tr>
<td>2007/08</td>
<td>NZ</td>
<td>19.93</td>
<td>10.16</td>
<td>6.26</td>
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<tr>
<td></td>
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<td>12.58</td>
<td>11.83</td>
<td>6.73</td>
<td>4.04</td>
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</table>

Notes: Boat age, Engine age and electrical equipment age are all in years. Boat length is in meters.
Appendix B.3

Map of the Northern and Southern Zone Rock Lobster Fisheries, showing the respective Marine Fishing Areas (MFAs).

Figure B.1: The Northern and Southern Zones and Marine Fishing Areas (MFAs) in the South Australia rock lobster fishery.

Note: The numbered boxes are data collection map codes. (Source: SARDI publication, SARDI Research Report Series, No. 588, 2011)
Appendix C

Proofs Related to Chapter 5

Proof 1

The Long-run decision.

We re-state the Hamiltonian (5.5) as follows, and consider the necessary, first order, conditions.

\[ H = e^{-\delta t} (pqE_{it}B_t - c - \gamma) E_{it} + e^{-\delta t} \lambda_t \left[ rB_t \left( 1 - \frac{B_t}{K} \right) - qE_{it}B_t - (n - 1)qB_{jt}B_t \right] \]

The necessary conditions of the Hamiltonian are

\[ e^{-\delta t} (pqB_t - c - \gamma) - e^{-\delta t} \lambda_t qB_t = 0 \]

and

\[ e^{-\delta t} pqE_{it} + e^{-\delta t} \lambda_t \left[ r - \frac{2r}{K} B_t - qE_{it} - (n - 1)qE_{jt} \right] = -e^{-\delta t} [\dot{\lambda} - \delta \lambda_t], \]

which reduce to

\( (pqB_t - c - \gamma) - \lambda_t qB_t = 0 \) \hspace{1cm} (C.1)

and

\[ pqE_{it} + \lambda_t \left[ r - \frac{2r}{K} B_t - qE_{it} - (n - 1)qE_{jt} \right] = -[\dot{\lambda} - \delta \lambda_t] \] \hspace{1cm} (C.2)
We consider the symmetric steady-state equilibrium. We thus focus on the steady-state, where $\dot{B}_t = 0 = \dot{\lambda}$. Steady-state variables are marked with tilda. Then $\tilde{B}$ and $\tilde{E}$ satisfy

$$ r \left( 1 - \frac{\tilde{B}}{K} \right) - nq\tilde{E} = 0 $$

implying

$$ \tilde{E} = \frac{r}{nq} \left( 1 - \frac{\tilde{B}}{K} \right). \quad (C.3) $$

The steady-state assumption implies

$$ \tilde{\lambda} = \frac{pq\tilde{B} - c - \gamma}{q\tilde{B}} \quad (C.4) $$

By symmetric steady-state it implies

$$ \delta = \frac{pq\tilde{E}}{\tilde{\lambda}} + \left[ r - 2r\frac{\tilde{B}}{K} - nq\tilde{E} \right] $$

Substituting for $\tilde{\lambda}$ from (25) yields

$$ \delta = \frac{pq^2\tilde{B}}{pq\tilde{B} - c - \gamma} \tilde{E} + \left[ r - 2r\frac{\tilde{B}}{K} - nq\tilde{E} \right] \quad (C.5) $$

Finally we substitute for $\tilde{E}$ in (26) from (24), and make the necessary algebraic re-arrangements to get

$$ \delta = \frac{r}{n} \left( 1 - \frac{\tilde{B}}{K} \right) \frac{pq\tilde{B}}{pq\tilde{B} - (c + \gamma)} - \frac{r\tilde{B}}{K}. $$

Further re-arrangement of this gives the modified golden rule (MGR) in the form

$$ \delta = -\frac{r\tilde{B}}{K} + \frac{r}{n} \left( 1 - \frac{\tilde{B}}{K} \right) \frac{pq\tilde{B}}{pq\tilde{B} - (c + \gamma)} $$

which the MGR in Equation (5.6).

This is the usual MGR except that instead of $c$, there is $c + \gamma$. □
Proof 2

The short-run decision.

We re-state the Hamiltonian of Equation (5.7) below and give the necessary conditions

\[ H = e^{-\delta t} \left[ pqE_{it}B_t - cE_{it} - \frac{m}{2}(E_{it} - \bar{V}_i)^2 \right] + e^{-\delta t} \lambda_t \left[ rB_t \left( 1 - \frac{B_t}{K} \right) - qE_{it}B_t - \sum_{j \neq i} qE_{jt}B_t \right] \]

The necessary conditions of this Hamiltonian are

\[ pqB_t - c - m \left( E_{it} - \bar{V} \right) - \lambda tqB_t = 0 \quad \text{(C.6)} \]

and

\[ pqE_{it} + \lambda_t \left[ r \left( 1 - \frac{2B_t}{K} \right) - qE_{it} - (n - 1)qE_{jt} \right] = -[\dot{\lambda} - \delta \lambda_t] \quad \text{(C.7)} \]

As before we consider the symmetric steady-state equilibrium, and focus on the steady-state, where \( \dot{B}_t = 0 = \dot{\lambda} \). Steady-state variables are marked with hat. Then \( \dot{B} \) and \( \dot{E} \) satisfy

\[ r \left( 1 - \frac{\dot{B}}{K} \right) - nq\dot{E} = 0 \]
which implies

\[ \dot{E} = \frac{r}{nq} \left( 1 - \frac{\dot{B}}{K} \right). \tag{C.8} \]

From the above the steady-state assumption it implies

\[ \dot{\lambda} = \frac{pq\dot{B} - c - m\dot{E} + m\ddot{V}}{q\dot{B}} \tag{C.9} \]

and

\[ \delta = \frac{pq\dot{E}}{\dot{\lambda}} + \left[ r - \frac{2r}{K} \dot{B} - nq\dot{E} \right]. \]

Substituting for \( \dot{\lambda} \) from (30) gives

\[ \delta = \frac{pq^2\dot{B}}{pq\dot{B} - c - m\dot{E} + m\ddot{V}} + r \left( 1 - \frac{2\dot{B}}{K} \right) - nq\dot{E}. \tag{C.10} \]

We substitute for \( \dot{E} \) in (31) from (29), and make the necessary re-arrangements to get the modified golden rule (MGR) in the form

\[ \delta = -\frac{r\dot{B}}{K} + \frac{r}{n} \left( 1 - \frac{\dot{B}}{K} \right) - \frac{pq\dot{B}}{pq\dot{B} - c + m\ddot{V} - \frac{mr}{nq} \left( 1 - \frac{\dot{B}}{K} \right)} \tag{C.11} \]

which the MGR in Equation (5.7). □
Proof 3

Total derivative of Equation (5.6) with respect to $\tilde{B}$ and $\gamma$ is

\[
0 = \left\{ -\frac{r}{K} - \frac{r}{nK} \frac{pq \tilde{B}}{pq \tilde{B} - (c + \gamma)} + \frac{r}{n} \left( 1 - \frac{\tilde{B}}{K} \right) \frac{pq \left[ pq \tilde{B} - (c + \gamma) \right] - pq \tilde{B}pq}{\left[ pq \tilde{B} - (c + \gamma) \right]^2} \right\} d\tilde{B} \\
+ \left\{ \frac{r}{n} \left( 1 - \frac{\tilde{B}}{K} \right) \frac{pq \tilde{B}}{\left[ pq \tilde{B} - (c + \gamma) \right]^2} \right\} d\gamma,
\]

which implies

\[
\frac{d\tilde{B}}{d\gamma} = -\frac{r}{n} \left( 1 - \frac{\tilde{B}}{K} \right) \frac{pq \tilde{B}}{\left[ pq \tilde{B} - (c + \gamma) \right]^2} > 0
\]

for $\gamma > 0$, $\pi > 0$, and $F(B) > 0$. So for costs lower than $\gamma$, if $\gamma$ falls (to zero even), $B$ goes down (i.e., will be lower than $\tilde{B}$). □

Proof 4

The derivative of Equation (5.10) with respect to $\hat{B}$ is

\[
\frac{d\hat{\pi}}{dB} = pq \frac{r}{nq} \left( 1 - \frac{\hat{B}}{K} \right) - (pq \hat{B} - c) \frac{r}{nqK} + m \left( \frac{r}{nq} \left( 1 - \frac{\hat{B}}{K} \right) - \hat{V} \right) \frac{r}{nqK}
\]
which, after rearranging and substituting in 
\[ \hat{E} = \frac{r}{nq} (1 - \frac{\hat{B}}{K}) \]
gives Equation (5.11).

For Equation (5.11) to be positive we require
\[ pqK - c - m(\hat{E} - \bar{V}) - 2 \left[ pq\hat{B} - c - m(\hat{E} - \bar{V}) \right] > 0 \]  
(C.12)

The lowest steady-state level of profit occurs at the bionomic level of biomass, that is, where
\[ pq\hat{B} - c - m(\hat{E} - \bar{V}) = 0 \]
At this biomass, (C.12) will certainly be true. The highest steady-state level of profit occurs when the discount rate is zero. In this case we can solve the modified golden rule (5.8) for \( \hat{B} \) explicitly and subsequently \( \hat{E} \)

\[
\hat{B} = \frac{pq^2K + ncq - nmq\bar{V} + mr}{(n + 1)pq^2 + \frac{mr}{K}}
\]
\[
\hat{E} = \frac{r}{nqK} \cdot \frac{npq^2K - ncq + nmq\bar{V}}{(n + 1)pq^2 + \frac{mr}{K}}
\]

Substituting these into (C.12) and rearranging we get
\[ \frac{(n - 1)pq^2}{(n + 1)pq^2 + \frac{mr}{K}} \left( pqK - c + m\bar{V} \right) > 0 \]

As (C.12) is true for both highest and lowest steady-state profits, it must be true for other levels of profit. □
Proof 5

The total derivative of Equation (5.8) with respect to $\hat{B}$, $p$ and $\tilde{V}$ is

$$0 = -\left\{ \frac{r}{K} + \frac{r}{nK} \frac{pq\hat{B}}{pq\hat{B} - c + m\tilde{V} - m\frac{r}{nq} \left(1 - \frac{\hat{B}}{K}\right)} + \frac{r}{n} \left(1 - \frac{\hat{B}}{K}\right) \frac{pq\left(c - m\tilde{V} + m\frac{r}{nq}\right)}{\left[pq\hat{B} - c + m\tilde{V} - m\frac{r}{nq} \left(1 - \frac{\hat{B}}{K}\right)\right]^2} \right\} d\hat{B}$$

$$-\left\{ \frac{r}{n} \left(1 - \frac{\hat{B}}{K}\right) \frac{q\hat{B}\left(c - m\tilde{V} + m\frac{r}{nq} \left(1 - \frac{\hat{B}}{K}\right)\right)}{\left[pq\hat{B} - c + m\tilde{V} - m\frac{r}{nq} \left(1 - \frac{\hat{B}}{K}\right)\right]^2} \right\} dp$$

$$-\left\{ \frac{r}{n} \left(1 - \frac{\hat{B}}{K}\right) \frac{pq\hat{B}m}{\left[pq\hat{B} - c + m\tilde{V} - m\frac{r}{nq} \left(1 - \frac{\hat{B}}{K}\right)\right]^2} \right\} d\tilde{V}$$

Under the assumption that it is costly to put forth effort for whatever size vessel, then

$$c - m\tilde{V} + m\frac{r}{nq} > 0$$

$$c - m\tilde{V} + m\frac{r}{nq} \left(1 - \frac{\hat{B}}{K}\right) > 0$$

With the assumption of non-negative profits this means all terms in parentheses will be positive and hence

$$\frac{d\hat{B}}{dp} < 0 \text{ and } \frac{d\hat{B}}{d\tilde{V}} < 0.$$

\[\square\]