

A Portfolio Approach for the New Zealand Multi-Species Fisheries Management

PhD Research Proposal

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Abstract

Marine species are reproducible resource. Maintaining the stock level of marine species and the sustainability of fisheries development become critical issues in current scientific research areas due to the explosion of human population and exacerbation of natural environment. The traditional method that protects the marine species is the single species approach which set maximum sustainable yield (MSY) to prevent over-harvest. However, with the development of technology and comprehension of marine science, the single species approach has been found obsolete and incapable of dealing with problems of severe depletion of fish stocks and escalation of fisheries confliction. Studies show that when regulations are species specific and species are part of a multi-species fisheries, the catch levels of different species are correlated which result in correlation of net return from each species. This paper employ financial portfolio into fisheries, treat fish stocks as assets, model the fishers' behaviour who face multiple targeting options to predict the optimal targeting strategies. This methodology is applied to New Zealand fisheries that are managed in Quota Management System (QMS) introduced in 1986. Species considered in this research are selected carefully based on two criteria. Efficient risk-return frontier will be generated that provides a combination of optimal strategies. Comparison between results and actual data will be presented. Potential explanations will be given so that further suggestions to fisheries can be made.

1. Introduction

Two-thirds of the surface of the Earth is covered by ocean and inland water. Marine systems have provided food and other natural resources for humans for thousands of years. Fish are a source of food; oil and other sources of energy are vital to modern society. However, with the development of technology and population explosion, human activities have inevitably created tremendous impacts on the marine ecosystem and these activities have jeopardized the sustainable use of oceans. Unfortunately, this problem was not fully recognised and clearly understood until the over-harvesting problem had endangered the survival of many marine species. Recently, many scientists and economists have acknowledged that institutional interventions should be made to manage human activities and protect the marine resource so that the services they provide can be sustained for future generations.

The conventional method aimed at preventing the over-harvesting of fish is the single species approach. Under this approach, harvest limits and species biomass are estimated using a biological model. Economic profitability is not integrated into the decision making process as seen by the use of maximum sustainable yield (MSY) to limit the catch level. A large number of papers have extended this single species approach by incorporating further instruments, such as right-based management system, and so on.

Recently, the single species approach has been found to be an inadequate guide for setting harvest levels while maintaining ecosystem health. The main reason for this criticism is that marine systems change as a result of a combination of human activities and environmental variation. Marine species should be considered as a complex rather than a collection of species in isolation. As a result, it is argued that ecosystem-based fisheries management (EBFM) should be used because it recognises the correlation among multi-species. Ecosystem-based fisheries management is a novel integrated approach that provides a framework for understanding and managing human activities that affect the marine system. The overall goal of EBFM is to restore

and maintain an ecosystem in a healthy, productive and resilient¹ condition; integrate species and human activities so as to provide sustainable ecosystem services to humans. Although there is a consensus about the validity and necessity of EBFM, there is little literature on how to operationalize it. Implementing EBFM requires both market information and biological science.

My research proposal is based on the thesis that financial portfolio theory can be applied to EBFM so as to investigate both species interaction and profitability. Portfolio theory can incorporate the inter-dependence among different species, consider risks that result from the uncertainty of profits and provide an optimal strategy for marine species. Implementing the portfolio approach requires not only economic and ecological knowledge, but also administration rules such as those embodied in New Zealand's quota management system (QMS).

New Zealand's QMS was introduced in 1986. Under this rights-based system, individual firms hold a share of harvest quota which is set by Ministry of Fisheries at the beginning of each fishing season. Since 1986, the Ministry has relied exclusively on biological models and the stock assessment process for setting the allowable harvest. This approach does not provide adequate information on the economic impact of adjusting the allowable harvest.

My research employs financial portfolio theory to determine the most appropriate harvest level for fishing firms governed by the QMS. In principle, under the QMS, each fishing firm cannot harvest an amount over its quota endowment. The first model in this research investigates the optimal harvest under this binding constraint. However, the introduction of the annual catch entitlement (ACE) and deemed value regime into the QMS in 2001 enables fishing firms to harvest in excess of their rights. The second model examines the optimal harvest when this constraint is absent. Each model will determine the optimal harvest portfolio given market conditions. The portfolio approach will also generate an efficient frontier which consists of a combination of optimal strategies based on firm manager's risk tolerance.

¹ Resilience is a measure of the ability of systems to absorb changes and persist.

2. Background Information

2.1. Single species approach

The predominant approach used to manage fish stocks is to treat species independently. Exploited species are regarded in isolation from their surrounding environment. Marine habitat, predators and prey of the target species, and interactions with other components in ecosystem are ignored.

2.1.1. Schaefer Model

The most commonly used model in single species analysis is the *Schaefer model* after biologist M.B. Schaefer (1957). Before this model can be applied, it is necessary to estimate the logistic growth function of the marine species.

Let $x = x(t)$ denote the population size of fish species at time t . Suppose that both the birth rate b and mortality rate m are proportional to population size. We write $n = b - m$ as for the *net proportional growth rate*, and obtain the continuous-time stock dependent growth model

$$\frac{dx}{dt} = G(x) - h(t) = bx - mx = n \cdot x, \quad (1.1)$$

where $G(x)$ represents the natural growth rate of the population, and $h(t)$ represents the rate of removal or harvesting.

This simplified model implies that when $G(x) \equiv h(t)$, the population x remains at a constant level. In other word, the natural growth rate $G(x)$ provides a sustainable yield that can be removed from the marine system without varying the population level x .

Under ideal conditions with a relative small population size, the forces of maturation and reproduction are supposed to dominate. With abundant food and living space,

individuals breed fast. However, this trend cannot continue infinitely. As the population level becomes larger, food and space scarcities start to decrease the growth rate. At some point there will be a natural equilibrium between these positive and negative factors of growth and a natural population size would be formed. The simplest model that can be used to illustrate this effect would be

$$n(x) = n(1 - x/K)$$

so that

$$\frac{dx}{dt} = n(x)x = n\left(1 - \frac{x}{K}\right)x. \quad (1.2)$$

This is the logistic equation, proposed firstly by P.F. Verhulst in 1838. The positive constant n is usually called the *intrinsic growth rate* which refers to the proportional growth rate for small population size; K is the environmental *carrying capacity* which is assumed to be positive and constant. This model indicates that the proportional growth rate $n(x)$ is a decreasing function of x , specifically,

$$n(x) = \frac{G(x)}{x}. \quad (1.3)$$

Figure 1 illustrates the relationship between population size x and growth rate $\frac{dx}{dt}$.

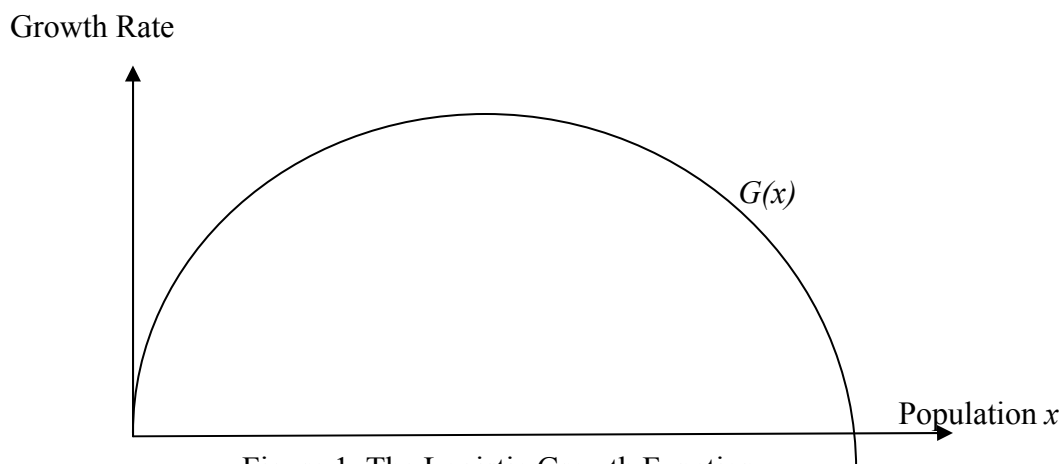


Figure 1. The Logistic Growth Function

In fisheries statistics, fishing effort is often used to measure the total number of vessel-days per unit time. With the introduction of fishing effort E , an assumption is made that catch-per-unit-effort is proportional to biomass level:

$$h = aEx, \quad (1.4)$$

where a is called the catchability coefficient, E denotes the fishing effort.

Substituting both (1.3) and (1.4) into Eq. (1.1), the harvesting model will be

$$\frac{dx}{dt} = G(x) - h(t) = n(x) \cdot x - aEx = n \left(1 - \frac{x}{K} \right) x - aEx. \quad (1.5)$$

In equilibrium, $dx/dt = 0$. Solving this equation, we have a unique nonzero equilibrium x , given by

$$x^* = K \left(\frac{n - aE}{n} \right).$$

Plugging x^* into the harvest equation we obtain, the equilibrium harvest sustainable yield

$$Y^* = h^* = aEK \left(\frac{n - aE}{n} \right). \quad (1.6)$$

The parabola in Figure 2 illustrates this equation.

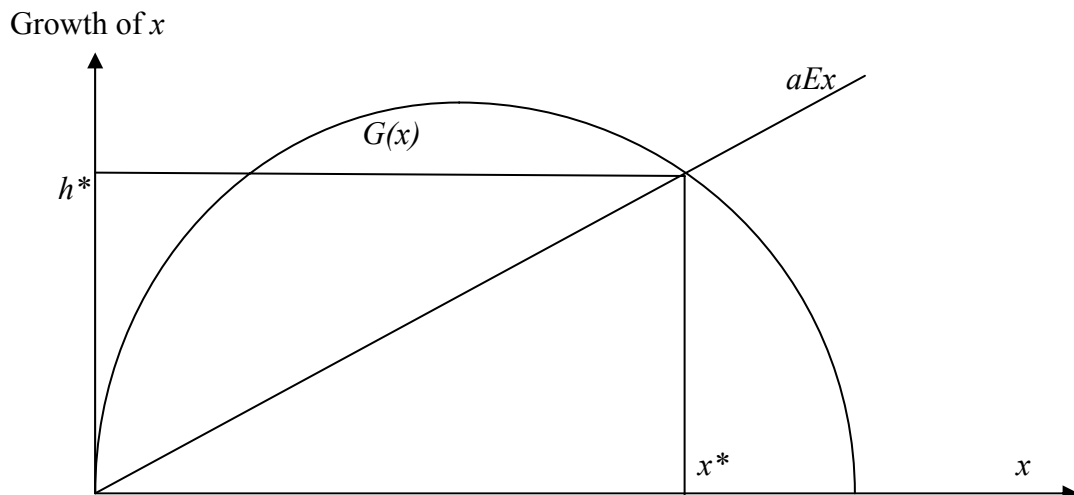


Figure 2. Logistic Model with Constant Fishing Effort E .

Harvest, as represented by equation (1.6), is a quadratic function of fishing effort E . Sustainable yield increases firstly as fishing effort increases; then after a critical point, sustainable yield starts decreases as E increases. Solving this equation, we obtain the critical point $x^* = K/2, E = n/2a$.

MSY is determined when fishing effort $E = n/2a$. If the fishing effort reaches $E = n/a$, population size shrinks to zero, the species is extinguished. Figure 3 presents the yield-effort curve which emphasizes the yield corresponding to different levels of fishing effort E . This is a more useful illustration because E can be considered a choice variable of fisheries management.

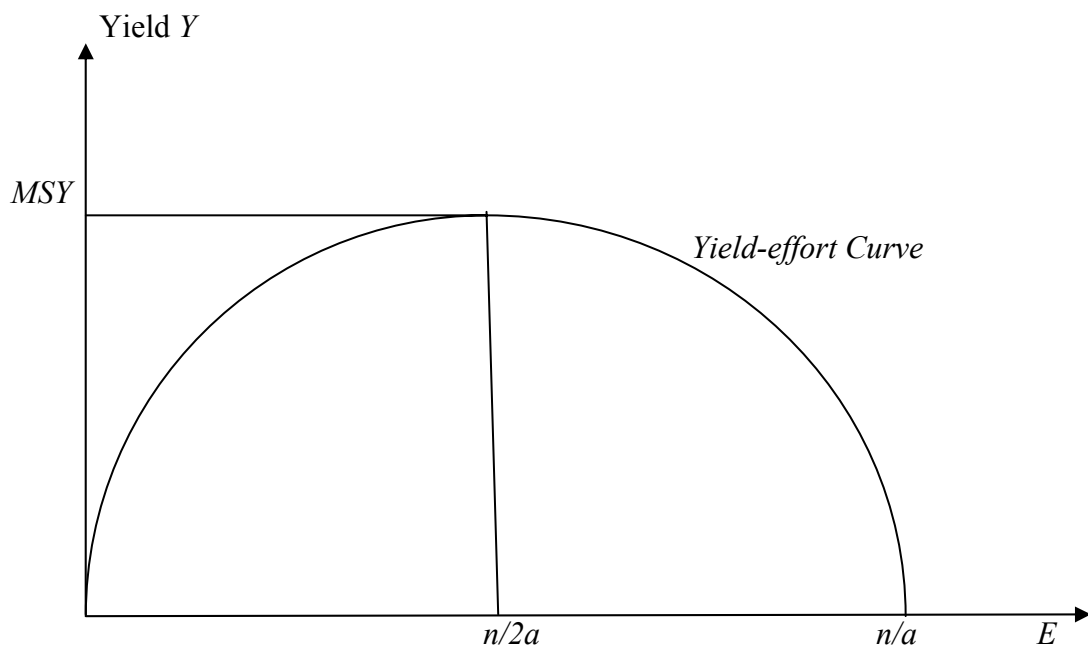


Figure 3. Yield-effort Curve for the Schaefer Model

The model derived above does not incorporate any economic factors. In order to develop an economic model, it is necessary to determine the market price for both fishing effort and harvested species. Let us assume that the harvested fish are sold on a market with a constant and given price. We also assume that each unit of effort has a constant and given opportunity cost. This cost represents the market value of unit effort. These assumptions enable us to build the revenue and cost function depicted in Figure 4.

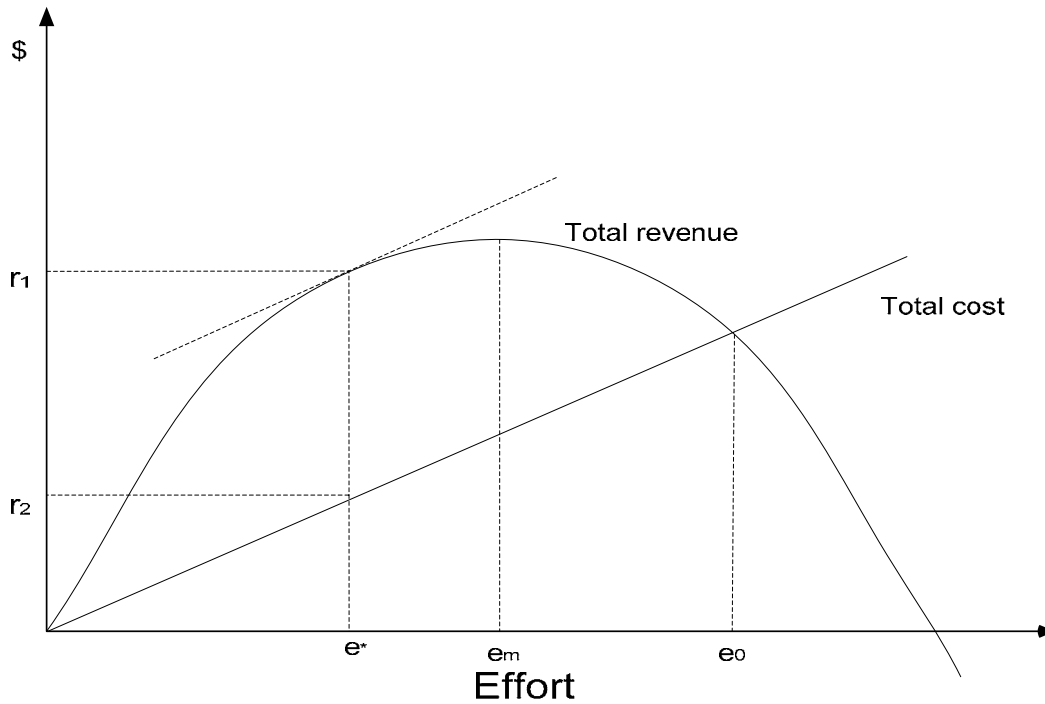


Figure 4. Simple Bio-economic Model

The effort yield curve in Figure 3 multiplied by the unit price of the harvested fish gives us the total revenue curve in Figure 4. Thus the inverted U-shape is preserved. The straight line represents total cost. It starts at the origin and rising to the right with a slope representing the opportunity cost of a unit of effort. In this simple model the net income refers to the net social benefit corresponding to any effort level. In Figure 4, this is depicted by the distance between total revenue curve and total cost line. This distance is maximised at effort level of e^* because at this level the slope of total cost is equal to the slope of total revenue, which means that marginal revenue equals to marginal cost at this effort level, and net benefits at this point are equal to $(r_1 - r_2)$. It is easy to see that at any other effort level, net benefits-the distance between the two curves-would be smaller than at e^* .

2.1.2. The Inadequacy of Single Species Approach

Biologically, the single species MSY approach mentioned above does not accommodate interactions among species that comprise aquatic communities. Economically, MSY fails to account for profitability. Furthermore, MSY-led policies

ignore the problem of what is the appropriate mix of species and population size in an ecosystem; how to address the difficulty of the existence of uncertainty affecting species contributions; and how to operationalize the ecosystem management approach with suitable policies. Since traditional models do not account for the ecosystem dynamics of species interactions, fish stocks cannot be managed effectively (Robert 1997, Bax 1998, Arnason 2000, Caddy and Cochrane 2001, Manickchand-Heileman *et al.* 2004).

Bycatch – where non-target fish are caught incidentally – also challenges the feasibility of single species approach. According to Gislason *et al.* (2003), bycatch can change the trophic² structure of the entire ecosystem. For example, more than 80% of the annual mortality of white marlin resulted from the harvest of swordfish and tuna by U.S. longline fisheries (Foundation file, 2001). This resulted in white marlin being listed as an endangered species by the U.S. government. The nature of the marine system and the inherent non-selectivity of fish gear imply that the single species approach is not consistent with ecological principles and not profitable from the perspective of fisheries management.

Many prominent biologists, economists, and mathematicians have objected to the use of the single species approach based on MSY in fisheries management. According to May *et al.* (1979), isolated consideration of MSY cannot provide sufficient information for management, although it is a useful point for the discussion of single species management. The MSY concept by its self, is not sophisticated enough to “serve as a valid operational objective for the management of most living resource stocks” (Clark, 1990). Arnason (1998), in one of his articles dealing with transferable quota, indicated that single species approach may result in serious mistakes in the interpretation of the observed data, and subsequently forecasting and policy recommendations. Larkin (1977) even wrote a poem to ridicule the institutionalized policy of single species in many countries and spoke of a “farewell” to MSY.

² The word “trophic” refers to feeding. “Trophic level” describes the feeding level in a food web. The first trophic level includes species known as the primary producers, e.g. photosynthesizers.

2.2. Ecosystem-Based Fisheries Management

Ecosystems are complex natural units that provide a flow of services to commercial fisheries. Fishing has a direct influence on ecosystems; on the other hand, ecosystems influence commercial fishing. Therefore, it is necessary to manage fisheries as an ecosystem. ESBM is a holistic approach to maintain ecosystem³ quality and sustain associated benefits (Larkin, 1996; Ecosystems Principles Advisory Panel, 1999; Brodziak and Link, 2002). Specifically, EBFM can be defined as “*an approach that takes major ecosystem components and services – both structural and functional – into account in managing fisheries... its goal is to rebuild and sustain populations, species, biological communities and marine ecosystems at high levels of productivity and biological diversity so as not to jeopardize a wide range of goods and services from marine ecosystems while providing food, revenues and recreation for humans*” (US National Research Council, 1998).

Generally, there are three dynamic ecosystem issues to consider: trophic linkages, bycatch, and multispecies substitution. The relationship between predator and prey species is commonly positive. If the landings of a predator species increase, then the prey species population will increase as well. Consequently the harvest of prey species will increase because its predator is undergoing bigger removal. Given that the life cycle of these two species is different, it would be expected that this negative effect will take place with a lag. For example, in a research for the relationship between Carite⁴ (predator) and honey-shrimp (prey) in the Gulf of Paria (Dhoray & Teelucksingh, 2007), Trinidad, the most appropriate lag length was found to be two years in this system.

The relationship between target and bycatch species is negative. If there is an increase in the target species landings, then the landings of bycatch species will fall because the increased mortality rate will result in a reduction in the harvestable amount of bycatch species. Multispecies substitution effects occur when two valuable species can be caught by same harvesting methods. If two different species are harvested by

³ An ecosystem is a dynamic complex of microbes, plants, animal and physical environmental substances that interact with each other.

⁴ Carite is the local name for the Spanish mackerel *Scomberomorous brasiliensis*.

the same technique, e.g. gillnet, then the proportion of species with greater commercial value will exceed the less valuable species because additional fishing effort will be allocated deliberately to more valuable species. This implies that there is a negative relationship between these two species because every harvesting method has limited capacity. An increase in the landings of more valuable species will decrease the landings of less valuable species. Previous research indicates that both the bycatch effect and substitute effect occur with periodic lags and the duration of this lag will depend on the species and their living environments.

Decision making based on EBFM differs from single species management. Single species management aims at not harvesting more than the growth of the target specie; In contrast, EBFM aims to ensure that the total biomass removed in all fisheries does not exceed the ecosystem productivity, after considering other components of the same marine community, e.g. correlation between target and bycatch species, trophic interactions among predator and prey species, and habitat variance.

Recently, the importance of uncertainty has been recognised in fisheries management. Traditional single species management models compare the advantages and disadvantages between an open access fishery and revenue maximizing fishery. However, there are certain unpredictable fluctuations that cause uncertainty in commercial fisheries. Fluctuations in market prices can have a major impact on profit. The price of fuel, the major input of fishing, also varies over time. Another problem in fisheries management is the identification of cause and effect in an ecosystem (Gislason et al. 2000). Human activities, distance and afar, and natural community variability can change the ecosystem structure and function. These factors result in uncertainty when analysing harvesting strategies. Government policy can also create risky returns. Currently, management rules are based on a single-species approach. Regulations that treat each species separately are implausible because these species interact with others in the ecosystem. Other rules, such as catch limits create incentives for fishers to discard their harvest; area-closure rules can work to decrease profits and increase variability of profits.

After the evaluation of potential consequences, regulators and management agencies can take actions under the suggested policies. Several tools can be taken to manage a fishery where risk is present (Hilborn *et al.* 2001):

(1) Technical methods, e.g. gear type, engine horsepower, mesh size, fishing areas and seasons closures, e.g. Marine Protected Area (MPA), etc.

(2) Input controls, e.g. number, type and size of vessels, restrictions on days-at-sea, etc.

(3) Output controls, e.g. harvest control, transferability of individual and community quota, bycatch limits, etc.

These controls are not used in isolation. Instead, they are normally applied simultaneously. The simplest form of risk management is risk sharing. Insurance is an example in which risk of loss is shared with insurance purchaser. Another option for risk sharing is the diversification mechanism of a portfolio approach that has been extensively used in financial markets.

Risk in the fishery can be assessed and reduced, but cannot be avoided. If we want to maintain the stability of the fishing community, we have to understand that it is important to manage risk even though we have seen little evidence of the implementation of risk management in current fishery policies. In addition, we should realize that current ecological theories have limited explanatory power; further research is necessary to address the problem of uncertainty and provide scientific advice on fisheries management.

2.3. Portfolio Approach

Financial portfolio theory provides a framework for dealing with species interactions in fisheries management and addresses the problem of uncertainty. The portfolio approach is based on the portfolio theory developed by Nobel-Prize winner Herry

Markowitz (1952)⁵. Markowitz's portfolio analysis is a mathematical tool to determine how to select the optimum proportion of assets in a portfolio for investment. This technique has been extensively used in financial markets. Applying portfolio theory to fisheries management and policy is a recent development.

2.3.1. Portfolio Tools.

A portfolio is a combination of investments that achieves the highest possible expected return given a level of risk (Grinblatt and Titman, 2001). This theory is based on the assumption that investors are mean-variance optimizers. Portfolio holders are assumed to be risk-averse; they prefer lowest possible return variance of an investment return. Thus **asset allocation** is very beneficial to portfolio managers who want to decide how much of their portfolio should be assigned for each investment including stocks, real estate, equities, etc. To lessen risk, portfolio managers should hold many securities to balance their investment by diversification among different securities. When a portfolio manager adds more stocks in portfolio, the additional stocks diversify the portfolio if these stocks do not move together (co-vary) with the existing stocks in the portfolio.

There are three characteristics of each security that determine the mean and variance of return of a portfolio:

1. The **mean return (expected return)** of each security.
2. The **variance** of the return of each security.
3. The **covariance** between the return of each security and the returns of other securities in the portfolio.

The expected return is calculated by multiplying the return outcomes with the probability of the outcome and sum up all the weighted outcomes. For a portfolio which consists with N stocks, the portfolio return is:

⁵ His analysis was originally presented in a paper: "Portfolio Selection", *Journal of Finance*, March 1952, pp. 77 – 91. Later Markowitz extended and elaborated his research and published it in a book, *Portfolio Selection*, Cowles Foundation Monograph 16 (New York: John Wiley & Sons, Inc, 1959).

$$\tilde{R}_p = x_1 \tilde{r}_1 + x_2 \tilde{r}_2 + \dots + x_N \tilde{r}_N = \sum_{i=1}^N x_i \tilde{r}_i,$$

where \tilde{r}_i is the return of individual stock i , and x_i is the corresponding proportion of stock i .

The variance of a return is the expected value of squared return net of expected return:

$$\text{var}(\tilde{r}) = E[(\tilde{r} - \bar{r})^2] = \sigma(\tilde{r})^2,$$

where \tilde{r} is the return of the investment; \bar{r} is the expected return of the investment and it is constant; $\sigma(\tilde{r})$ is the standard deviation of return \tilde{r} .

Covariance is a measure of relatedness of different investments. The general formula to calculate the covariance between two returns is:

$$\sigma_{12} = E[(\tilde{r}_1 - \bar{r}_1)(\tilde{r}_2 - \bar{r}_2)].$$

Given the information described above, it is possible to calculate the variance of the return of a portfolio. Specifically, the variance formula of a portfolio which consists of N stocks is:

$$\sigma_p^2 = \sum_{i=1}^N \sum_{j=1}^N x_i x_j \sigma_{ij},$$

where σ_{ij} is the covariance between the returns of stocks i and j .

Independent assets have zero covariance (Markowitz, 1959). If the returns of assets move together, then these assets are **positively correlated** with **positive covariance**. In this situation, combining these assets – for example, fishing technology and ecology – can increase expected aggregated returns. But it may not reduce risk. Instead, positive covariances will raise the portfolio variance. In contrast, asset returns that move in opposite directions are **negatively correlated** and have **negative covariance**. Portfolio variance will be reduced with the combination of negatively correlated

individual assets. Portfolio variance will be less than the sum of variance of individual assets.

By plotting all feasible combination of assets in two-dimensional space with mean return on the vertical axis and standard deviation on the horizontal axis, we have the **feasible set** of portfolios. Figure 5 illustrates the feasible set in a return-variance quadrant. In this figure, the upper-left or “northwest” boundary of this feasible set is known as **mean-variance efficient frontier**. This frontier is the most efficient trade-off between the mean and variance. Given the fixed level of variance, combination of assets on the efficient frontier gives the maximized expected return. Similarly, given the fixed level of expected return, portfolios on the efficient frontier minimize variance. Portfolios that offer smaller expected return for the same variance are dropped from consideration.

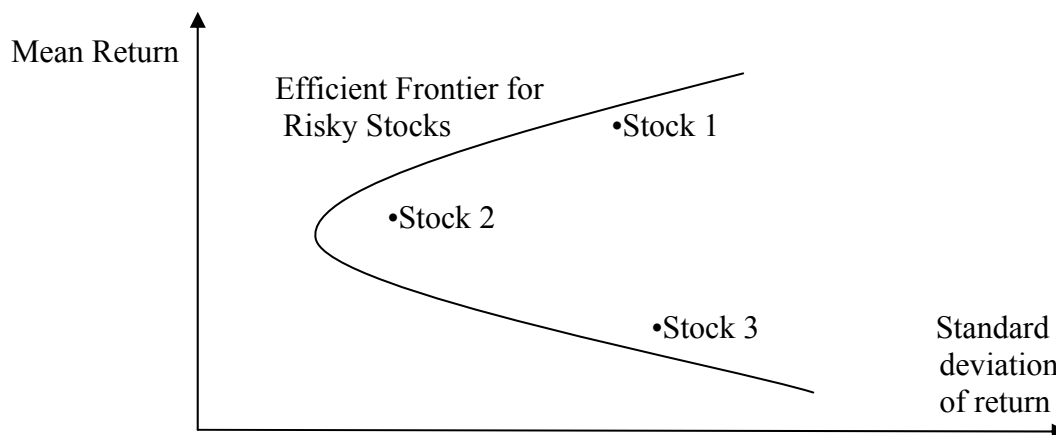


Figure 5. The Feasible Set

2.3.2. Portfolio Analysis in Multi-Species Management.

Portfolio analysis can be applied to either financial securities or real assets to find the most profitable combination of stocks given their individual return and risk properties. Naturally, fish species co-exist in ecosystem, and are most often caught by unspecialized gear. Harvesting one species can therefore affect the stock of other species. Portfolio theory systematically evaluates all feasible combinations of species which are joined by harvesting technology and ecology to find the optimal set that

generates the highest aggregate return for a given level of risk. When harvesting revenues are correlated among species, portfolio theory is suitable in multi-species fisheries that exhibit joint productive characteristics.

However, the portfolio approach does not completely replace the single species approach outlined above. Instead, it complements existing models. Portfolio theory explicitly recognizes that fish species are risk-bearing capital assets that can yield long term revenues to fisheries. By changing fishing effort, it is possible to manipulate the population and diversification of fish stocks to desired levels and improve the aggregate return from exploitation of a fish community.

There are two complementary parts that contribute to the implementation of portfolio theory to the multi-species fisheries management (Edwards et al. 2004). The first part systematically evaluates the trade-off between fishery benefits and risks resulting from environmental, market, and institutional uncertainties. Under this framework, fish stocks are treated as real assets that can provide economic benefit indefinitely. The contribution of a fish species and its collateral effects on other species is evaluated as an aggregate return to society. The second part comprises the property right institutions that create entry rules and assign harvesting rights (quota) to fishers in order to sustain the viability of fisheries.

2.4. The Quota Management System

New Zealand is a pioneer in the world for using individual transferable quota (ITQ) in fisheries management. Although many countries have implemented ITQs, no other country uses this system to the same extent as New Zealand does. The quota management system (QMS) was introduced in 1986 to manage commercial species in New Zealand marine system. The setting of QMS is based on ITQ rights operating within an administered total allowable catch (TAC). The objective of employing QMS is to enhance profitability and to ensure that New Zealand's fish resources are sustainably utilised through direct control of harvest levels. The QMS is widely regarded as one of the leading fish management tools in the world.

At the beginning of each fishing season, the Ministry of Fisheries states what quantity of each quota species can be caught. Decisions are based on stock assessment information supplied by the Ministry of Fisheries and on consultation with interested groups such as the commercial fishing industry, recreational fishers, Maori and other conservation groups. Allowable harvest levels are worked out using the concept of MSY illustrated in Figure 3, which is the largest average annual catch level that can be harvested without reducing the stock's productive potential. Legislation requires administrators to manage stock levels toward MSY, adjusted by social and economic considerations. Records of annual landings, estimates of catch per unit effort, estimates of recreational harvest are made available to the stock assessment consultative process.

The TAC includes the total harvest from commercial sector, recreational and customary fishing. Under the Fisheries Amendment Act 1986 S10 and Fisheries Act 1996 Ss20, when allocating catch levels, the Minister must firstly make an allowance for customary catch. Once the customary allowance is determined, the remainder of the TAC is then allocated between commercial sector and recreational sector. Under current policy, neither of the two sectors has priority in legislation; both sectors have to be considered simultaneously.

A total allowable commercial catch (TACC) is set after making an allowance for recreational fishing and customary harvest, which we define as the total allowable non-commercial catch (TANC). The TACC is a limit on the catch that can be taken by the commercial sector only. Thus the $TAC = TACC + TANC$. The TAC covers all mortality to a fish stock caused by human activity. Once the TACC is set for the year, fishing rights are distributed to quota owners in proportion to their quota holdings. Thus, individual firms hold an entitlement to harvest a share of the TACC defined as a percentage of the TACC⁶. Quota holdings are standardised to one hundred million shares per fish stock.

In 2001, Annual Catch Entitlements (ACE) were introduced into QMS. ACE rights are assigned to quota holders based on the share of total quota they hold and the

⁶ Under the Fisheries Amendment Act 1990 S15.

TACC. Given the TACC in a specific year, the kilogram equivalent of each quota share is calculated. This quota share, which is defined as ACE, is allocated to quota holder on the first day of fishing year. Therefore, the ACE determines the total tonnage of species that the quota holder can harvest within the fishing season. The introduction of ACE has distinct benefits because it separates the harvest rights between the current rights and long-term owners. Quota owners can sell their current harvesting entitlement (ACE) while retaining long-term ownership. Individual fishers can purchase ACE for a particular fishing season without a change of quota ownership.

Because ITQ are transferable, they will, in principle, be owned by more efficient firms. Rights are defined in perpetuity, divisible, transferable, and bankable. Under the QMS, individuals who hold quota rights are free to sell as they wish. There is no pre-approval required for the trade. Also there is no limit on the number of times that the quota can be sold. Quota is divisible so that owners can sell parts of quota they hold. Before a buyer can use the quota, the trade must be registered. Not all quota holders wish to sell or fish their quota; instead, many of quota owners sell their ACE allowing others to fish their quota allocation in the current fishing period. By selling their ACE, quota owners are able to gain income from their quota rights. Quota rights cannot be owned by foreign companies. Moreover, there is a limitation on the quantity of quota holdings. Under the 1986 Amendment Act, no one can hold more than 20% of the quota for any Quota Management Area (QMA) and fish stock.

The deemed value mechanism, also introduced in 2001, provides an incentive to balance catch against ACE. Deemed values are a financial penalty that fishers have to pay for the harvest that is not covered by ACE. Under the Fisheries Amendment Act 1990, fishers pay a deemed value for the over-harvest not covered by ACE. Deemed values are usually set higher than the ACE price to discourage over-harvest; however a higher deemed value provides an incentive for dumping. Therefore, setting the appropriate level for deemed value is a critical problem faced by Ministry of Fishery.

3. Literature Review

The overall objectives of EBFM are to maintain the health of marine ecosystem and sustainable development of associated fisheries. According to Pikitch *et al.* (2004), the main purposes of EBFM are to:

1. Avoid degradation of the ecosystem, as assessed by environmental quality and ecosystem status.
2. Minimize irreversible risk related to species structure and ecosystem.
3. Produce long term socioeconomic benefits without compromising the ecosystem.
4. Develop and accumulate ecosystem knowledge that enables us to understand the potential consequence of human's fishing activities.
5. Adopt a suitable precautionary management.

Although the precautionary approach and EBFM have been widely discussed, there is very little literature about how these two ideas can operate together in fisheries management (Sanchirico *et al.* 2007). Both require ecologists and economists to consider constraints which represent system interactions and uncertainty. The standard approach to incorporate uncertainty relies on the risk neutrality of social planner. However, based on the Reed (1974, 1979) model, the optimal solution under single-species case is to shut down the fishery entirely for a certain period and re-open it after the ecosystem has re-covered to provide new harvestable stocks. This policy violates the goal that renewable marine resources should generate a sustainable flow of profits to fishers. Unnecessary closure would reduce fishers' welfare. The standard approach which can deal with species interactions is to build structural models that determine the TAC for each harvestable species within the ecosystem. However, this kind of model is data intensive and costly to develop. Moreover, the optimal solution will be sensitive to even small variance in biological or economic parameters (Clark 1990).

When regulations are species-specific and the species is part of a multi-species fishery, the production function will join species. According to Kirkley and Strand (1988), significant economic linkages and technology interactions co-exist in multi-species fisheries; separability of inputs factors and output among species is not plausible. Management focused on individual species cannot prevent over-harvesting and avoid economic waste. Thus, in order to implement a multi-species approach, we must understand the various components within an ecosystem, and consider their impacts in the ecosystem.

There are three sorts of risk associated with fisheries management: availability of fish and therefore catch, changes of market price, and regulations (Pontecorvo, 1986). Biological assets, such as fish species, are not manufactured by humans, and therefore uncontrollable by human activity. The population of fish stocks fluctuate naturally due to shifting ocean-atmosphere phenomenon such as *El Niño – Southern Oscillation* (ENSO) which impact the survival of larval and juvenile fish, abiotic factors which affect recruitment (Myers, 1998; Rothschild, 2000), and trophic interaction such as predation (Bailey and Houds, 1989; Rice et al., 1993). Furthermore, fishing activity affects species composition and biomass structure. These factors make the availability of fish stocks highly unpredictable.

Therefore, it is necessary to develop new techniques that incorporate risk assessment by calculating possible consequences of different combinations of management measures and data treatment so that we can evaluate how much improvement can be achieved relative to the traditional approach.

Quota Management System

After the introduction of QMS in New Zealand, the quota ownership structure changed rapidly (Falloon, 1993). Between 1986 and 1988, 15,580 quota covering 453,000 tonnes were sold, and 3,417 quotas covers 253,000 tonnes were leased (Sissenwine and Mace, 1992). The sum of these quota transactions is much greater than the total amount of quota allocated in these years. This result indicates that some

quota must have been either sold or leased many times. The industry consolidation during the first three years (Bess, 2000) presumably leads to a more efficient fishery with the removal of less competent operators (Sissenwine & Mace, 1992).

Before the introduction of the QMS, it was argued that small companies are not capable of competing with large firms and will be forced out of fishery, and this will lead to concentration in the industry. Connor (2000 and 2000b) found that quota ownership rapidly concentrated in the first several years. This aggregation tapered off in later years. Connor's finding was supported later by Newell and Sanchirico (2003). Newell and Sanchirico (2003) not only investigated the concentration of quota rights ownership, but also examined the changing structure of fishery to find that it is the medium size of companies, rather than small companies, that exited the industry.

Portfolio Approach

It is observed that the expected returns along the efficient frontier increases at a decreasing rate. This implies that the one additional unit of aggregate return can be achieved by sacrificing more units of obtained variance after the point of unitary elasticity⁷. Therefore, in the analysis of multi-species fisheries management, it is plausible to decrease the proportion of species that contribute more to return variability after considering their contribution to expected returns and interaction with other species. For example, predator species on the top of food web tend to live longer and their population normally remain stable (Beddington et al. 1984). Moreover, consumers generally place high value on these upper trophic level fish. These complementary characteristics illustrate that the low natural mortality species will count for more importance in a portfolio.

There are two advantages of portfolio approach which make it more suited to be used in ecosystem-based management. One difficulty in applying the EBFM is that risk-

⁷ Elasticity is the ratio of the proportional change in one variable with respect to proportional change in another variable. In economics, unitary elasticity refers to the situation where a change in one variable causes an equal or proportional change in another variable. So, unitary elasticity is equal to one in absolute value.

return trade-offs are inevitable (Sanchirico et al. 2007), and there is little guidance on how these trade-offs are to be set and compared (Sanchirico and Hanna 2004). The portfolio approach provides an empirical basis for evaluating tradeoffs. Another advantage is that it is possible to incorporate additional constraints into the objective function to achieve different ecological, economic, and social objectives.

Several characteristics of multi-species fisheries should be considered when we apply portfolio model in the real world. First, it is usual for gear to harvest more than one fish species. According to Kelleher (2005), each year 8% of all harvested fish are thrown overboard and wasted. Bycatch is impossible to eliminate completely due to the co-existence of species in nature and unspecified technology (Berger et al, 1989). Managing the multi-species fisheries without considering bycatch can result in severe ecological and economic problems.

Second, the value of a stock can be affected by more than one factor. The traditional method is to use biomass or age-class (cohort). However, gender ratios or population genetics can also contribute to the value of a stock (Cheung, 1970). Species habitat characteristics are another important factor which influences the stock valuation and fishing technology can change the habitats in beneficial or deleterious ways (Edwards et al. 2004). Altogether, these attributes complicate the evaluation of fish stocks within an ecosystem.

Third, market price is another crucial element when considering the economic value of a fish stock. In multi-species fisheries, different species are usually treated as partial substitutes by consumers and seafood producers. Therefore, market price of one species is a function of not only itself, but also other species in this ecosystem. New Zealand imports seafood from overseas markets and exports most of its harvest to the world (Lock and Leslie, 2007). Due to the relatively small size of the domestic market and production capacity, international market prices inevitably have a strong influence on domestic markets.

Finally, McGlade (1989) suggested that within a portfolio framework, property rights institutions should evaluate fish assets in the ecosystem and resolve conflicts among stakeholders on an ecosystem scale. Property rights, by definition, are the entitlements

of holders for the usage of resources which are accepted by society and protected against encroachment by others (Demsetz, 1998). In fisheries management, property right institutions define the relationship between fishers and fish stock in an ecosystem. With adequate property rights, regulators can prevent over-harvest and conserve fish stocks within an ecosystem. On the other hand, environmental uncertainties and stock fluctuations in an ecosystem also require the regulations to be flexible and adaptive to the variance of fisheries. Under this situation, collecting new information from the ecosystem is essential for regulators to make prompt decisions to meet the requirement of shifting multi-species fisheries.

According to Elton and Gruber (1995), average risk of a combination of assets is totally different with risk of an individual asset. Therefore, there is a potential advantage of risk reduction in multi-species management if the value of assets in a portfolio move in different directions. In single species MSY analysis, the most obvious concern is the tradeoff between mean and variance of returns (Beddington and May, 1977; May et al., 1978; Silver, 1982). But in multi-species management analysis, the critical point is the covariance among different species (Edwards et al. 2004).

EBFM Analysis

The idea of applying the portfolio approach to multi-species fisheries management is novel, and few papers provide insights about this approach. Four prominent papers are presented below.

3.1. Arnason (2000)

Arnason was probably the first economist to study the management of multi-species fisheries within the context of ecosystem. In 2000, he proposed an economic model in which manages fishing activities are managed so as to maximize economic yield. In his paper, an aggregate ecosystem fisheries model was developed. His model focused

on aggregate representations of an ecosystem. A habitat variable was used to influence the growth of fish biomass. Harvest is expressed as a function of biomass and fishing effort which in turn determines harvesting costs. The objective was to maximise the present value of economic rents from the fisheries.

Two distinct results are found. First, it may be optimal that certain fisheries have zero or negative profits in order to increase the aggregate economic contribution from the ecosystem. Second, it is necessary to modify single species harvesting rules for certain species even though the species do not reveal biological interactions. Arnason reckoned that ecosystem fisheries are extremely complicated, and consequently very difficult to determine and implement optimal management rules. He recommended that ITQ approach rights are a promising option for ecosystem fisheries management because the fishery will operate efficiently subject to TACs under this system.

3.2. Edwards et al. (2004)

In this paper, fish stocks are treated as environmental capital that yields permanent benefits to society. Therefore, the economic value of a renewable nature resource is the present value of net returns (revenues minus costs). More specifically, the economic value of a fish stock i in the current period ($t = 0$) is the accumulation of future income from harvest which is discounted by a rate ρ .

Edwards et al. (2000) use technology H , an exogenous variable. The resulting revenue function of the j th unspecialized technology is

$$v_{j,t} = \sum p_t(y_{i,t})y_{i,t} - c(y_{1,t}, \dots, y_{i,t}, \dots, y_{n,t}, x_{1,t}, \dots, x_{i,t}, \dots, x_{n,t} | H_j),$$

which is subject to the appropriate growth rate equation

$$\frac{dx_{i,t}}{dt} = g(x_{1,t}, \dots, x_{i,t}, \dots, x_{n,t}) - y_{i,t}.$$

Based on the analysis of Elton and Gruber (1995), the expected value of the portfolio's return is:

$$E(R_t^P) = \sum h_i \int f(R_{i,t}) R_{i,t} df ,$$

where $f(R_{i,t})$ is the relative frequency on the distribution of returns of stocks i ; h_i is the fraction of the portfolio's aggregate return comprised by stock i . The variance of the portfolio is:

$$\sigma_t^{P2} = \sum h_i^2 \sigma_{i,t}^2 + \sum \sum h_i^2 h_k^2 \sigma_{ik,t} ,$$

where $\sigma_{ik,t}$ is the covariance of returns between assets i and k . The covariance can be decomposed as $\rho_{kj,t} \sigma_{i,t} \sigma_{k,t}$, where $\rho_{ik,t}$ is the correlation coefficient between asset i and k , $\sigma_{i,t}$ and $\sigma_{k,t}$ are standard deviations of asset i and k respectively.

Edwards et al. (2000) apply this model to an ecosystem with three species. These species are linked by a trophic chain. One species is the prey species, and the other two are predators. The harvested fish are sold in a competitive market where the species are treated as partial substitutes. Thus the trophic interaction and price relations results in correlation among species. All possible stock portfolios are calculated and plotted as a set of points in a two-dimensional expected return and variable space. Accordingly, a risk-return efficient frontier is presented with minimum variance or maximum expected returns along the outer envelope.

Since the expected return along the efficient frontier increases at a decreasing rate, the gain in the expected value of total returns is less than the increase in variance after the point of unitary elasticity. Therefore, it may be profitable to thin out the stocks that contribute the most to return variability. That is, given well-defined objectives and ecological and economic constraints, populations of low-value or high-risk species can be deleted from the portfolio in order to balance the expected return against return variability. On this basis, the portfolio manager would be expected to manage fewer species than are currently exploited. This paper also emphasised the necessity of property rights in multi-species fishery management.

3.3. Perruso et al. (2005)

A significant aspect of this model is that spatial decision making provides important information to firm managers for optimal firm behaviour. Thus, a linkage between the *ex ante* production level and spatial decision-making is presented. More specifically, the optimal targeting portfolio approach is based on a pelagic longline vessel operating on the trip level.

A theory of a fisher's behaviour is considered in this model. The fisher selects the catch of species that generates the maximised expected utility by evaluating different affordable harvest choices within a portfolio. This implies that there is a probability distribution of the portfolio's net return. It is assumed that the fisher's initial wealth is zero so that *ex ante* targeting decision will not be affected by existing wealth. Since the targeting decision is made at the trip level, net trip level return will explain a fisher's behaviour.

If the expected utility function is assumed to be monotonic and strictly concave, then a preference for expected returns and an aversion to variance in returns is guaranteed. The analysis above indicated that expected utility is a function of the mean, variance and skewness of net revenues and risk is due to production uncertainty.

The portfolio targeting model considered the optimal targeting strategy by allocating effort (trip) toward a set of harvestable species based on a trade-off between expected returns and variance of returns. The optimal targeting problem is to minimize the variance of trip level revenue subject to constraints that the expected value of trip level return is greater than a specified level return β . Changing the value of β in the quadratic function yields an efficient frontier of harvest strategies. Each point on the efficient frontier minimizes the variance of trip level revenue given a specified level of returns.

Perruso et al. suggest that the portfolio approach is a valuable tool for individual firm managers when choosing targeting strategies and modifying their policy in accordance with government requirements. However, to be more practical, this

portfolio model may need to incorporate more information to make long-run decisions, such as species-specific regulations in certain fisheries.

3.4. Sanchirico et al. (2006)

A value-at-risk method is adopted in their model, and fish prices are assumed to be constant in seafood market. The target strategy is to find the optimal weight of revenue for each species which represents the percentage of mean revenue of a particular species contribute to the portfolio. Total expected revenue is the weighted average of revenues from each species.

Revenues of certain species are correlated. The optimization problem is to minimize the variance of total profit. The target function is subject to a constraint that the expected value of total revenue is greater than target level of revenue which is determined by the firm manager's willingness to accept risk.

Sustainability constraints are also imposed in their model which restricts the revenue weight to a certain range. First, the non-negative value of revenue weights ensures that each weight is feasible. Second, the ecosystem has limited physical capacity to generate revenue, the upper limits of each weight ensures that catch does not exceed the current fish stock or allowable fraction of harvest. The upper bound of constraint is set according to rule that the *ex post* catch levels will not exceed the *ex ante* sustainable levels and consequently a precautionary safeguard applies. In their study, the sustainability parameter was treated as exogenous by ecosystem managers who choose the optimal catch of species to meet the target revenue and subject to the sustainability parameter.

By using the full covariance matrix, ecosystem frontiers for 1980, 1990, and 2000 were presented. A single species frontier was also derived by ignoring species interactions. Putting these two frontiers in one graph, they found that the frontiers do not overlap with each other which imply that the species' correlations do play an important role in the ecosystem. Moreover, by allocating data into different periods, they found that the full covariance frontier lies above the diagonal covariance frontier

in all graph, indicating that - given target revenue - the ecosystem approach causes less risk than the single species approach due to the potential negative correlation of certain fish species.

4. Research Proposal

4.1. Objectives

The primary aim of this research is to find the optimal harvest level of different fish species in static state for a specific fishing firm by using the portfolio approach. To conduct this research, several objectives are listed below:

1. Two economic models will be derived. The first model will investigate the optimal harvest when the TACC is a binding constraint for fishing firm; the second model will relax this constraint.
2. These models will be applied to a firm governed under New Zealand QMS to generate efficient frontiers.
3. I will examine the optimal results, and compare it with actual data to give possible policy suggestions for both the firm and Ministry.

By adopting the portfolio approach, the manager can choose the optimal catch level of each fish species subject to ecosystem sustainability and capability. A point on the efficient frontier represents an optimal harvest for each species within this portfolio. Fishing firms can use the portfolio approach to choose the species and quantities so as to mitigate potential risk associated with harvest. By operating on the frontier, firm managers ensure that they are gaining the most revenue for a given level of risk (variance) within the ecosystem.

4.2. Method

This research adopts the firm manager's point of view for the maximization of total profit. It has been argued that profit may not be the best measure to evaluate the value of an ecosystem. Ecosystem stability or social welfare (trophic-level contributions to economic value) can be alternative objectives. However, the time-series data of these two targets are not complete or not available. It is commonly accepted that the most

suitable economic model is determined by the availability of data (Turvey 1964; Hilborn & Mangel 1997). Since the approach in this research is empirical, results will depend on the availability of data. Therefore, targeting profit will provide a better metric to measure the trade-off between the expected value and variability in fishery revenues.

Profit data not only indicate the performance of firms during fishing season which includes employment and efficiency of fishing activities, but also other important information, e.g. fish stock size. On the other hand, the variance of profit is expensive to the individual fisher. They have limited ability to earn income outside of fisheries but have considerable expenditure to cover. Varying revenue cannot guarantee constant income for fishers; it will degrade their living standard and deteriorate viability of fisheries. Variance of revenue also send misleading signal to capital investment and increase the risk of returning. Therefore, maximising the expected value of profit or minimising the variance of profit will be the target function in this research.

Three methods can be used for portfolio analysis:

1. Graphical method;
2. Calculus method;
3. Quadratic programming (QP).

The principal advantage of graphical methods is that it is easier to grasp conceptually. The disadvantage of it is that it cannot handle portfolios containing more than a few stocks. The calculus method is capable to handle portfolios containing large number of securities. Also, it is simple to manipulate. However, the calculus solution technique cannot handle inequality constraints. Quadratic programming (QP) is the most useful method in handling large portfolio problems that involves inequality constraints. With this method, each security or asset in a portfolio can be determined to optimize the portfolio. This technique has been extensively applied in large number of:

1. *Efficient Production*. Maximization of profit with linear production functions and linear marginal cost.
2. *Convex programming*. Minimization of a convex function subject to linear constraints.
3. *Regression*. Finding the best least-square fit to given data.
4. *Portfolio Analysis*. Choosing a combination of random variables given expected value and variance.

For a portfolio which consist a set of n assets, the data inputs are:

1. n expected returns.
2. n variances of returns.
3. $(n^2 - n)/2$ covariance.

Applying portfolio approach into fisheries is rare and new to economists. There is risk that profit may vary over a certain range. The harvesting profit cannot be guaranteed with 100 percentages. The firm manager has to bear the risk that in a year the total profit may vary. If the manager wants to reach a certain point of total profit, he or she has to bear a risk that with certain probability the profit may not reach that point. Then we can draw an efficient frontier in a return-risk quadrant. On the frontier, a certain point of expected value of profit corresponds to a certain point of variance which represents the risk. Moreover, a point on the efficient frontier represents a portfolio, which consists of harvests of different species. Given a manager's risk-aversion ratio, locating the efficient frontier is possible. Points on that frontier mean that what's the maximum profit the manager can obtain given a certain level of risk (variance in this situation).

There are many factors that affect the variance of profit. A large proportion of New Zealand's harvest is exported, e.g. Japan, Europe, or North America⁸. New Zealand is a small country and takes world price as given. Foreign markets usually influences local sea product price, resulting in the local price unpredictable. The harvesting cost also reflects information about the fishery, for example, advance within fishing

⁸ According to Ministry of Fisheries, 90% of total harvests are exported to foreign markets.

technology, employment, oil price, or administration regulation, such as, restriction of fishing season, exclusion of fishing area, and so on. Marine system influence fish stocks. Fish population is often affected by predation, disease, or competition from other species. Marine currents, temperature oscillation, abundance of nutrition also change fish stock. All these environmental forces influence stock size, directly or indirectly influence catches levels and corresponding profits of fisheries. Due to the limitation of knowledge about the marine forces and stock sizes, it is extremely difficult to examine how these marine forces, fishing technology, regulations and market conditions affect the fisheries profits.

Therefore, it is necessary to find a variable that contains all the information. In this research, the ACE price which is determined by market price and harvesting cost is the appropriate variable that will be used to analysis fisheries profits. ACE price reflects the net return of unit harvest. The uncertainty of profit is represented by the fluctuation of ACE price. The varying ACE price reflects the changes of both market conditions and biological information.

From Francis and Archer (1979), the general formulation for calculating maximization of a **portfolio's return** is

$$V = \theta E(r_p) - \text{var}(r_p), \quad (5.1)$$

where r_p represents portfolio's return, it is the summation of every species's return in the portfolio; θ is the weight attached to a unit of expected return relative to a unit of variance. It is a positive constant and increasing with increased expected return. θ represents the firm manager's risk-aversion attitude to risk. Higher value of θ means the portfolio manager has more aggressive attitude. It is shown in Figure 6.

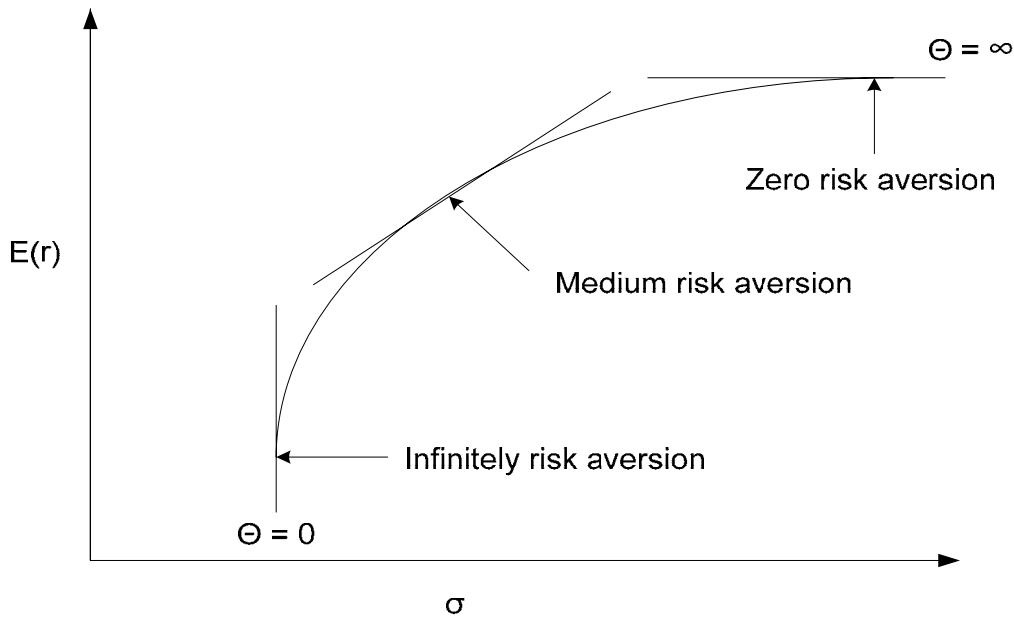


Figure 6. Efficient Frontier of Portfolio as θ varies

There are two main advantages of adopting portfolio theory compared with traditional optimization theory. First, traditional optimization only considers a single return from separate term while ignoring the correlations among terms. Portfolio theory incorporates the correlations and calculates the overall return from all terms. Second, the portfolio approach transforms the objective function from a linear profit function to a quadratic portfolio return function. With a linear objective function, the optimal results are generated by just choosing the bounded value of a choice variable in the constraint range; however, with the quadratic objective function, the optimal result will be selected carefully within the constrain range.

4.3. Model with Binding Constraint

For a firm manager, the choice variable is the catch level of species the firm is harvesting. By choosing the optimal harvest for each species, the firm manager aims at maximising the total profit of fisheries subject to its endowments of TACC.

4.3.1. Profit of fisheries

Suppose there are n species harvested in New Zealand fisheries.

Let q_i denote the harvest of species i . Then profit from harvesting species i is

$$\pi_i = (p_i - c_i) \cdot q_i,$$

where p_i denotes the landing price of species, c_i denotes the harvest cost of species i .

Let A_i denotes the ACE of species i , then

$$\pi_i = A_i \cdot q_i,$$

since the ACE price is determined by considering both landing price and harvest cost, it reflects the unit return of harvest.

Therefore, for the New Zealand fisheries, the total profit from harvesting all fish species is

$$\Pi = \sum_{i=1}^n \pi_i = \sum_{i=1}^n A_i \cdot q_i.$$

Let \bar{A}_i denotes the expected value of ACE price A_i , i.e.

$$E(A_i) = \bar{A}_i.$$

Thus the expected value of total profit is

$$E(\Pi) = E\left(\sum_{i=1}^n A_i \cdot q_i\right) = \sum_{i=1}^n E(A_i) \cdot q_i = \sum_{i=1}^n \bar{A}_i \cdot q_i. \quad (5.2)$$

Let σ_i^2 denotes the variance of A_i , σ_{ij} denotes the covariance between ACE price A_i and A_j , i.e.

$$\begin{aligned} \text{Var}(A_i) &= \sigma_i^2, \\ \text{Cov}(A_i, A_j) &= \sigma_{ij}. \end{aligned}$$

Then variance of the total profit is

$$\begin{aligned} \text{Var}(\Pi) &= E [\Pi - E(\Pi)]^2 \\ &= \sum_{i=1}^n \sum_{j=1}^n q_i q_j \sigma_{ij}.^9 \end{aligned} \quad (5.3)$$

Substituting (5.2) and (5.3) into the (5.1), the total harvesting return of fisheries with portfolio theory is

$$\begin{aligned} V &= \theta \cdot E(\Pi) - \text{var}(\Pi) \\ &= \theta \cdot \sum_{i=1}^n \bar{A}_i \cdot q_i - \sum_{i=1}^n \sum_{j=1}^n q_i q_j \sigma_{ij}. \end{aligned} \quad (5.4)$$

Then the objective function is

$$\text{Max}_{q_i, q_j} V = \text{Max}_{q_i, q_j} \left\{ \theta \cdot \sum_{i=1}^n \bar{A}_i \cdot q_i - \sum_{i=1}^n \sum_{j=1}^n q_i q_j \sigma_{ij} \right\}.$$

The choice variable q_i is subjected to the bound conditions

$$0 \leq q_i \leq TACC_i.$$

Given the TACC rights a fishing firm own for different species, the optimal results is only for this specific firm. It is noted that this model is suitable for any fishing firm in New Zealand fishery as long as TACC rights that a firm owns are given.

4.3.2. Feasibility of Model

⁹ For further derivation, please refer to appendix 1.

Let $a = \begin{pmatrix} \bar{A}_1 \\ \bar{A}_2 \\ \vdots \\ \bar{A}_n \end{pmatrix}$, then the transpose matrix of a , which is denoted by a' , is
 $a' = (\bar{A}_1, \bar{A}_2, \dots, \bar{A}_n)$.

Let $c = \begin{pmatrix} q_1 \\ q_2 \\ \vdots \\ q_n \end{pmatrix}$, then the transpose matrix of c , which is denoted by c' , is
 $c' = (q_1, q_2, \dots, q_n)$.

Let $D = \begin{pmatrix} \sigma_1^2 & \sigma_1\sigma_2 & \cdots & \sigma_1\sigma_n \\ \sigma_2\sigma_1 & \sigma_2^2 & \cdots & \sigma_2\sigma_n \\ \cdots & \cdots & \ddots & \vdots \\ \sigma_n\sigma_1 & \sigma_n\sigma_2 & \cdots & \sigma_n^2 \end{pmatrix}$,

Let $b = \begin{pmatrix} TACC_1 \\ TACC_2 \\ \vdots \\ TACC_n \end{pmatrix}$.

Then the **objective function** is transformed into

$$\text{Max } U = \text{Max } \{\theta l'c - c'Dc\}, \quad (5.5)$$

which subject to the bounded conditions

$$0 \leq c \leq b, \quad (5.6)$$

where D is a symmetric definite (n, n) matrix; c and b are n -column vectors.

This is a typical quadratic programming problem which involves maximizing a quadratic objective function (5.5) subject to linear inequalities (5.6).

There are a large number of papers about the quadratic optimisation problem since H. W. Kuhn and A. W. Tucker first investigated the stationary points in quadratic objective function subject to linear inequalities (Kuhn Tucker, 1951). Kuhn and Tucker formulated both the sufficient and necessary conditions for a saddle value of any differentiable function and applied them through a Lagrangian to find a maximum for a new differentiable function constrained by inequalities. Afterwards, many well-known procedures are available for solving the maximum problem in the concave case, e.g. Wolfe (1959) and Zoutendijk (1960). If the objective function is non-concave, the Kuhn-Tucker conditions are only necessary, the application of their method generally leads to only a stationary point which can be either a saddle point or a *relative* extremum. Orden(1963) provided both the necessary and sufficient conditions for the optimal solution of the non-concave quadratic maximum problem if the constraints are linear equations. Later, Ritter (1966) investigated the maximization of a non-concave quadratic objective function with linear inequalities as constraints. Zwart presented an algorithm for the global maximization of a convex function subjective to linear inequality constrains (1969), he argued that Ritter's method lacks of convergence and possibly gives rise to cycling. Zwart proposed a computationally finite algorithm and it was designed to converge rapidly since there are few local optima or the global optimum if significantly better than other local optima. In this research, the most suitable reference for the objective function is Frank & Wolfe's paper which published in 1956.

All approaches are computationally demanding. Currently, the most commonly used software for solving the quadratic optimization problems is **CPLEX**. Therefore, to obtain the optimal solutions, learning how to manipulate the **CPLEX** skilfully, or specifically, how to write computer code correctly is critical in the following research.

The efficient frontier can be derived by varying the value of risk-aversion attitude coefficient θ . By solving the model (5.5), the optimal q_i^* will be obtained which contains value of θ . Choosing a specific value of θ will generate a value for q_i^* . Given the value of q_i^* , the expected value of portfolio return can be calculated by multiplying the corresponding expected value of corresponding ACE price of species. The portfolio's variance can also be calculated given the variance of species' ACE prices. Then a point on a return-variance quadrant will be determined. Changing the

value of θ and following the same procedure, a set of optimal points will be attained. Combining these points will generate an efficient frontier which representing the optimal choice for firm manager.

4.4. Model Without Binding Constraint

Due to introduction of ACE and deemed value, fishers can harvest more than their entitlement. Fishers can either buy extra ACE rights from the quota market or pay deemed value to the government to cover their excess harvest. This implies fishers can harvest at any level they wish. In this situation, the TACC is not a binding constraint for fishing firm. This section investigates the optimal harvest without a TACC constraint.

Let A_i denotes the ACE price of species i , let DV_i denotes the deemed value of species i . Due to the limits of available amount of ACE, there is no guarantee that this firm can purchase enough ACE from market to cover its harvest over its original TACC endowment. Therefore, there is probability that this firm has to pay deemed value to cover its over-harvests. Based on the firm's previous records, it is possible to calculate the probability that this firm was able to purchase ACE, and the rest of the probability is the percentage that this firm has to pay deemed value.

Let α denotes the percentage that this firm can get the ACE, then we can get

$$\alpha A_i + (1 - \alpha) DV_i = T_i \quad (5.7)$$

where T_i represents the unit cost that this firm has to pay for an additional quantity of over-harvest of species i .

It is assumed that past data can be used to explain future behaviour. The New Zealand QMS has been functioning well in recent years. The equilibrium value of ACE price does not change dramatically year to year. Therefore, we can assume that previous period expected value of ACE price can be used as current period expected value of

ACE price. To obtain optimal harvests for current fishing season, the ACE price and deemed value in equation (5.7) will use previous periods expected value of ACE price and deemed value.

Let H_i denotes the harvest of this firm. Thus

$$H_i = TACC_i + q_i$$

where q_i denotes the over-harvest quantity of species i .

The purpose of this model is to find the optimal harvest of this firm. Since the $TACC_i$ is given at the beginning of this fishing season, it is an exogenous variable, so finding the optimal over-harvest q_i is equivalent to finding the optimal H_i in this model.

The profit of harvesting species i is

$$\begin{aligned}\pi_i &= p_i \cdot H_i - c_i \cdot H_i - T_i \cdot q_i \\ &= p_i \cdot (TACC_i + q_i) - c_i \cdot (TACC_i + q_i) - T_i \cdot q_i \\ &= (p_i - c_i) \cdot (TACC_i + q_i) - T_i \cdot q_i \\ &= A_i \cdot (TACC_i + q_i) - T_i \cdot q_i\end{aligned}$$

Let Π denotes the total profit of harvest over all species, then

$$\begin{aligned}\Pi &= \sum_{i=1}^n \pi_i \\ &= A_1 \cdot (TACC_1 + q_1) - T_1 \cdot q_1 + \dots + A_n \cdot (TACC_n + q_n) - T_n \cdot q_n.\end{aligned}$$

Let \bar{A}_i denotes the expected value of A_i , \bar{T}_i denotes the expected value of T_i , the expected value of total profit is

$$\begin{aligned}E(\Pi) &= E[A_1(TACC_1 + q_1) - T_1 \cdot q_1 + \dots + A_n \cdot (TACC_n + q_n) - T_n \cdot q_n] \\ &= E(A_1) (TACC_1 + q_1) - E(T_1) \cdot q_1 + \dots + E(A_n) \cdot (TACC_n + q_n) - E(T_n) \cdot q_n \\ &= \bar{A}_1 (TACC_1 + q_1) - \bar{T}_1 \cdot q_1 + \dots + \bar{A}_n \cdot (TACC_n + q_n) - \bar{T}_n \cdot q_n\end{aligned}$$

$$\begin{aligned}
&= \bar{A}_1 TACC_1 + (\bar{A}_1 - \bar{T}_1) \cdot q_1 + \dots + \bar{A}_n TACC_n + (\bar{A}_n - \bar{T}_n) \cdot q_n \\
&= (\bar{A}_1 TACC_1 + \dots + \bar{A}_n TACC_n) + (\bar{A}_1 - \bar{T}_1) \cdot q_1 + \dots + (\bar{A}_n - \bar{T}_n) \cdot q_n \\
&= C + (\bar{A}_1 - \bar{T}_1) \cdot q_1 + \dots + (\bar{A}_n - \bar{T}_n) \cdot q_n, \quad \text{since } \bar{A}_i \text{ and } TACC_i \text{ are given.}
\end{aligned}$$

The variance of harvesting return is

$$\begin{aligned}
\text{Var}(\Pi) &= E [\Pi - E(\Pi)]^2 \\
&= \sum_{i=1}^n \sum_{j=1}^n (TACC_i + q_i)(TACC_j + q_j)\sigma_{ij} + \sum_{i=1}^n \sum_{j=1}^n q_i q_j v_{ij} - 2 \sum_{i=1}^n \sum_{j=1}^n (TACC_i + q_i)q_j \omega_{ij},^{10}
\end{aligned}$$

where σ_{ij} denotes the covariance between A_i and A_j , v_{ij} denotes the covariance between T_i and T_j , ω_{ij} denotes the covariance between A_i and T_i .

The resulting quadratic programming problem is to minimize the variance of total return V subjective to a specified level of total return B , non-negative harvest of each species, and ecosystem capability:

$$\begin{aligned}
\text{Minimise } V &= \underset{q_i, q_j}{\text{Min}} \left\{ \sum_{i=1}^n \sum_{j=1}^n (TACC_i + q_i)(TACC_j + q_j)\sigma_{ij} + \sum_{i=1}^n \sum_{j=1}^n q_i q_j v_{ij} \right. \\
&\quad \left. - 2 \sum_{i=1}^n \sum_{j=1}^n (TACC_i + q_i)q_j \omega_{ij} \right\},
\end{aligned}$$

$$\text{subject to } E(\Pi) = \sum_{i=1}^n (\bar{A}_i - \bar{T}_i) \cdot q_i \geq B - C, \text{ and } 0 \leq q_i \leq R_i - TACC_i,$$

where R_i denotes the total biomass of species i in New Zealand marine system.

Varying the value of B in repeated optimizations generates an efficient frontier of harvest strategies. The firm manager's risk tolerance determines the value of B . A risk-averse manager would choose a high value of B . A manager who is confident about the future performance of firm would accept a low value of B .

¹⁰ For further derivation, please refer to appendix 1.

4.5. Data

In both models, data for four exogenous variables are needed for the analysis: TACC, ACE price, deemed value, and total biomass of each species.

ACE price data are available from Ministry of Fisheries (MFish). Data of ACE prices are routinely collected by MFish officers and fishing firm managers. Observing the ACE prices of each species will enable us to understand the varying trend in recent fishing years which contain both market and biological information.

Firm's share of TACC will also be collected. The data indicate the TACC endowment this firm own in this fishing year.

Transactions of ACE and deemed value payment will be collected from the firm's records. With these data, the unit cost of over-harvest in (5.7) will be calculated.

In New Zealand fisheries, the biomass level of each species is estimated in a certain range by using a specific biological method. The maximum level of biomass will be used in this research. The data range is available in MFish.

Given the data set describe above, several tasks can be conducted:

1. Given a data set of ACE prices, a covariance table will be calculated among different species. This table will indicate species with correlation. Possible explanations about these phenomena will be given by considering market information (e.g. substitution goods) or trophic level (e.g. predator-prey competition); and the intuitions that can be obtained from these results. Moreover, with the data set, it is possible to see whether some species can be reasonably omitted from the analysis.
2. An ecosystem mean-variance frontier will be derived by changing the value of risk-aversion attitude coefficient θ . Given specific value of θ , for example, low value ($\theta = 1$), medium value ($\theta = 50$), or high value ($\theta = 1000$), quantities or

shares of each species will be obtained. Consequently, the manager can manipulate the share of harvests of each species to generate the maximized profit based on his or her attitude to risk. Tables of *Share of harvests* with different value θ will be presented.

3. The ecosystem frontier above is derived by using the full covariance matrix which representing the correlation between different species. If only the diagonal-only covariance matrix is applied, then this strategy implies that only individual species variability are considered, species interactions are ignored. This ecosystem frontier will also be presented.
4. Comparing these two frontiers provides insight into the species correlation in New Zealand ecosystem. Theoretically, either frontier could have higher level revenue given a level of risk (variance). The relative position depends on the signs and magnitude of covariance among fish species. For example, in a two fish stock portfolio, if these two species are negatively correlated, then the frontier with full covariance matrix will have higher return or lower variance comparing with frontier with diagonal-only covariance matrix. In an n species portfolio, the relative frontier depends on the actual covariance of all fish stocks in the portfolio. This method will answer the question: whether the biological and economic interdependence should be taken into account to gain potential opportunity in the New Zealand ecosystem.
5. Actual return-variance points will also be plotted in the efficient frontier diagram. The distance between actual point and optimal point will be calculated in percentage terms. This will indicate how much improvement can be made. It is recommended that the distance can be used as ecosystem-based indicators (Brodziak & Link, 2002) so that knowledge of whether the ecosystem is over-harvested, fully invested, or under-harvested can be accumulated.
6. Given the optimal harvest of each species, share of species within a portfolio can be calculated. Since the correlations among different species are different, some species have zero correlation; it is plausible to eliminate certain species

which have little correlations with other species to investigate the variation of shares of species in the portfolio. For example, biologically, *red rock lobster* has low correlation with other species. This research will consider deleting this species in the portfolio to examine the share of other species and then compare those shares in the portfolio in which *red rock lobster* is included. Risk-aversion coefficient θ will be selected with specific value to calculate the share of species (e.g. $\theta = 100$).

4.6. Species selection

There are 97 marine species and species complexes in New Zealand's QMS. Including all species into this research is impractical. Perruso et al.'s paper analysed 8 species; Sanchirico and Smith chose 22 species in their research to examine these species' correlation and appropriate weight. Because the number and type of species the firm harvests are unknown at this stage, the firm is presumably harvesting some of the 97 species.

There are two criteria for the species selection. The first one is the commercial value of species. *Hoki, spiny red rock lobster, black paua & yellowfoot paua, arrow squid, orange roughy, snapper, ling, hake, scampi, and tarakihi* are the top 10 most profitable species in New Zealand. They contribute 78.7% of total commercial value in 2006¹¹. These ten most significant species will be included in this research. The second criterion for species selection is the availability of data. In this research, there are market and biological variables that require data to conduct econometric analysis. Species that lacks of these data will be absent in my research.

Therefore, based on these two criteria, 30 species will be considered. Appendix 2 is the list of potential species that will be analysed in this research.

4.7. Future work

¹¹ Data can be collected from Ministry of Fisheries website.

In financial market, risk-free asset exists. Asset-holders do not bear any risk for holding these types of assets. *N.Z. Government Treasury Bill* is one of example even it offers lower return than marketable stocks. In New Zealand fisheries, each fishing firm has an endowment of harvesting quota at the beginning of fishing season. The quota is tradable in market. Owners of quota can sell the harvesting right to other firms to gain certain returns. If we assume that the quota-holder can always find a *buyer* of ACE from the market, then the ACE return can be guaranteed all the time and then annual ACE return can be considered as a risk-free return in fisheries market. If these conditions are feasible, then the return-risk system can be represented by Figure 7.

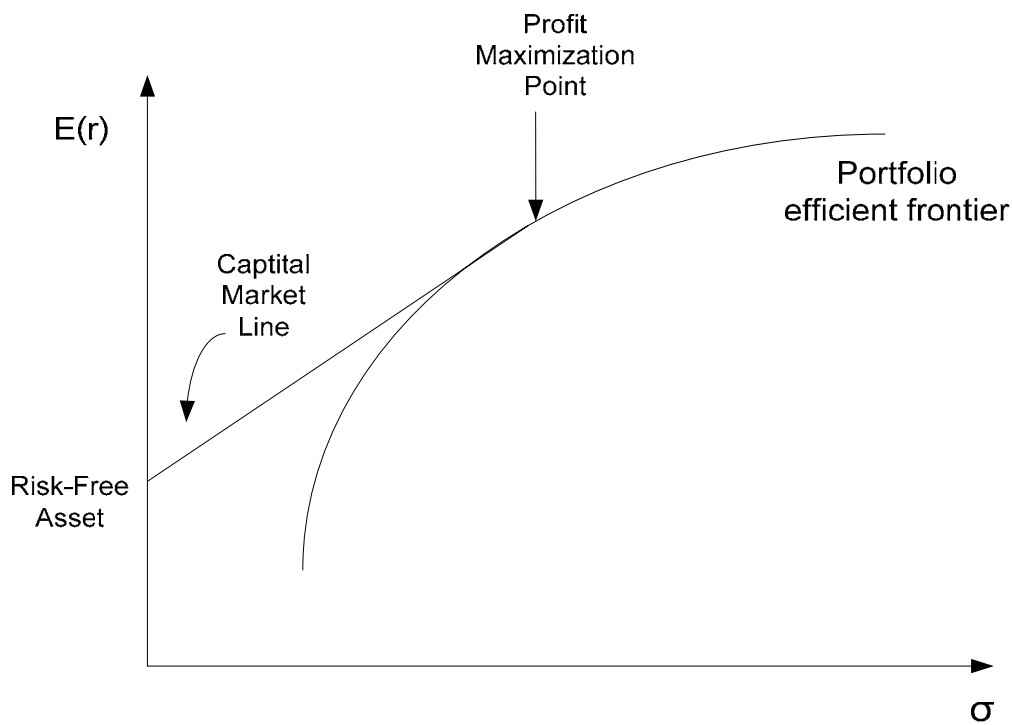


Figure 7. Combing Risky portfolio with a risk-free asset

Under this circumstance, the portfolio efficient frontier will be changed from that curve to the tangent line which I call the Fisheries Market Line (FML) corresponding to Capital Market Line (CML) in financial market. I will define and locate this tangent line in the future. LimDep is an appropriate software to estimate the FML.

4.8. Policy Suggestions

If the optimal results obtained from this research differ from the actual data, then the difference has to be explained so that valuable suggestions can be made to firm managers and/or fishery administrators. For example, if the firm manager adopts the first model and find that the quota rights the fishing firm holds are larger than the optimal results, then the manager can sell or lease redundant quota rights in the portfolio. If the optimal results are greater than the fishing firm's quota endowments, then is there any reason why this firm does not hold enough quota rights? Is there any regulation barrier that imposed on the firm preventing it acquire more quotas? Or does this firm itself have any disadvantage within its structure restricting it doing so? These questions will be investigated in further once the optimization models have been run and the FML estimated.

5. Outline of Thesis

1. Introduction

2. Single Species Approach

- 2.1. Schaefer Model
- 2.2. Maximum Sustainable Yield (MSY)
- 2.3. Inadequacy of Single Species Approach

3. Ecosystem-Based Fisheries Management

- 3.1. Precautionary Approach
- 3.2. Ecosystem-Based Fishery
 - 3.2.1. Definition and Objectives
 - 3.2.2. Metrics for Evaluation
 - 3.2.3. Instruments
- 3.3. Uncertainty
- 3.4. Risk Management
- 3.5. Summary

4. Quota Management System

- 4.1. Introduction and Operation
- 4.2. Total Allowable Commercial Catch (TACC)
- 4.3. Annual Catch Entitlement (ACE) and Deemed value

5. Portfolio Theory

- 5.1. Portfolio Tools
- 5.2. Portfolio Approach in Multi-species management

- 5.2.1. Defining of Asset and Return
- 5.2.2. Correlation Analysis
- 5.2.3. Risk Minimization

6. Modelling Fishery

- 6.1. Quadratic Programming
- 6.2. Model with Binding Constraint
- 6.3. Model without Binding Constraint

7. Empirical Study

- 7.1. Species Selection and Description
- 7.2. Analysis of Species Correlation in New Zealand QMS
- 7.3. Efficient Frontier Based on Risk-Aversion Attitude
- 7.4. Comparison between the presence of Species Correlation and Absence of Species Correlation
- 7.5. Investigation of deleting certain less correlated species
- 7.6. Comparison between Actual Data and Optimal Results
- 7.7. Risk-Free Return and Fisheries Market Line (FML)
- 7.8. Policy Suggestion

8. Summary and Conclusion

9. Reference

10. Appendix

6. Research Schedule

May 2007 – August 2007	<ul style="list-style-type: none"> • Review of literatures that are related with marine science and environment Economics. • Meet with officers from Ministry of Fisheries and establish contact with Ministry of Fisheries, Statistics of New Zealand, and NIWA
September 2007 – November 2007	<ul style="list-style-type: none"> • Learning financial portfolio knowledge and its application on environmental economics about natural resource • Contact MFish and other resource entities for the availability of data, both market and biological information, to determine what variables are feasible for the usage in this research • Comprehend the New Zealand Quota Management System
December 2007 – January 2008	<ul style="list-style-type: none"> • Development of a simply model, identify the objective function and corresponding constraints • Seek for appropriate algorithm for the model and appropriate computer software for the solving of model
February 2008 – March 2008	<ul style="list-style-type: none"> • Outline thesis chapters • Completion of research proposal
April 2008	<ul style="list-style-type: none"> • Submission of proposal
End of April, 2008	Presentation and defence of proposal to business school
May 2008 - October 2008	<ul style="list-style-type: none"> • Learning software CPLEX technique • Collection of more specific data from

	different resources.
November 2008 – March 2009	<ul style="list-style-type: none"> • Run model regression • Interpret results of model; compare it with current fisheries data • Extend model with further financial technique and compare it with old result
April 2009	<ul style="list-style-type: none"> • Visit Ministry of Fisheries and present model research in a seminar
May 2009 – June 2009	<ul style="list-style-type: none"> • Completion of all modelling and empirical work • Attendance of New Zealand Economics conference
July 2009 – October 2009	<ul style="list-style-type: none"> • Completion of thesis
November 2009 - January 2010	<ul style="list-style-type: none"> • Correction and revision of thesis
February 2010 – March 2010	<ul style="list-style-type: none"> • Preparation for oral exam • Submission of thesis
April 2010	<ul style="list-style-type: none"> • Oral exam

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Appendix

Appendix 1

Variance of profit with binding constraint:

$$\begin{aligned}
 \text{Var}(\Pi) &= E [\Pi - E(\Pi)]^2 \\
 &= E [l_1 q_1 + \dots + l_n q_n - E(l_1 q_1 + \dots + l_n q_n)]^2 \\
 &= E [l_1 q_1 - E(l_1 q_1) + \dots + l_n q_n - E(l_n q_n)]^2 \\
 &= E [l_1 q_1 - E(l_1) q_1 + \dots + l_n q_n - E(l_n) q_n]^2 \\
 &= E [q_1 (l_1 - E(l_1)) + \dots + q_n (l_n - E(l_n))]^2 \\
 &= E [q_1^2 (l_1 - E(l_1))^2 + \dots + q_i^2 (l_i - E(l_i))^2 + \dots + q_n^2 (l_n - E(l_n))^2 \\
 &\quad + q_1 (l_1 - E(l_1)) q_2 (l_2 - E(l_2)) \\
 &\quad + \dots \\
 &\quad + q_1 (l_1 - E(l_1)) q_i (l_i - E(l_i)) \\
 &\quad + \dots \\
 &\quad + q_1 (l_1 - E(l_1)) q_n (l_n - E(l_n)) \\
 &\quad \cdot \\
 &\quad \cdot \\
 &\quad \cdot \\
 &\quad + q_i (l_i - E(l_i)) q_1 (l_1 - E(l_1)) \\
 &\quad + \dots \\
 &\quad + q_i (l_i - E(l_i)) q_n (l_n - E(l_n)) \\
 &\quad \cdot \\
 &\quad \cdot \\
 &\quad \cdot \\
 &\quad + q_n (l_n - E(l_n)) q_1 (l_1 - E(l_1)) \\
 &\quad + \dots \\
 &\quad + q_n (l_n - E(l_n)) q_{n-1} (l_{n-1} - E(l_{n-1}))] \\
 &= q_1^2 E[(l_1 - E(l_1))^2] + \dots + q_n^2 E[(l_n - E(l_n))^2] \\
 &\quad + q_1 q_2 E [(l_1 - E(l_1)) (l_2 - E(l_2))] \\
 &\quad + \dots
 \end{aligned}$$

$$\begin{aligned}
& + q_n q_1 E[(l_n - E(l_n)) (l_1 - E(l_1))] \\
& + \dots + q_n q_{n-1} (l_n - E(l_n)) (l_{n-1} - E(l_{n-1}))] \\
= & q_1^2 \text{var}(l_1) + \dots + q_n^2 \text{var}(l_n) \\
& + q_1 q_2 \text{cov}(l_1 l_2) + \dots + q_1 q_n \text{cov}(l_1 l_n) \\
& + \dots \\
& + q_n q_1 \text{cov}(l_n l_1) + \dots + q_n q_{n-1} \text{cov}(l_n l_{n-1}) . \\
= & q_1^2 q_1^2 + \dots + q_n^2 q_n^2 + q_1 q_2 \sigma_{12} + \dots + q_n q_{n-1} \sigma_{nn} . \\
= & \sum_{i=1}^n \sum_{j=1}^n q_i q_j \sigma_{ij} .
\end{aligned}$$

Variance of profit without binding constraint:

$$\begin{aligned}
\text{Var}(\Pi) &= E(\Pi - E(\Pi))^2 \\
&= E \{ A_1(TACC_1 + q_1) - T_1 q_1 + \dots + A_n(TACC_n + q_n) - T_n q_n \\
&\quad - E[A_1(TACC_1 + q_1) - T_1 q_1 + \dots + A_n(TACC_n + q_n) - T_n q_n] \}^2 \\
&= E \{ [A_1 - E(A_1)] \cdot (TACC_1 + q_1) + \dots + [A_n - E(A_n)] \cdot (TACC_n + q_n) \\
&\quad - [T_1 - E(T_1)] \cdot q_1 - \dots - [T_n - E(T_n)] \cdot q_n \}^2 \\
&= E \{ [A_1 - E(A_1)]^2 \cdot (TACC_1 + q_1)^2 + \dots + [A_n - E(A_n)]^2 \cdot (TACC_n + q_n)^2 \\
&\quad + [T_1 - E(T_1)]^2 \cdot q_1^2 + \dots + [T_n - E(T_n)]^2 \cdot q_n^2 \\
&\quad + [A_1 - E(A_1)] \cdot (TACC_1 + q_1) \cdot [A_2 - E(A_2)] \cdot (TACC_2 + q_2) \\
&\quad + \dots \\
&\quad + [A_1 - E(A_1)] \cdot (TACC_1 + q_1) \cdot [A_n - E(A_n)] \cdot (TACC_n + q_n) \\
&\quad - [A_1 - E(A_1)] \cdot (TACC_1 + q_1) \cdot [T_1 - E(T_1)] \cdot q_1 \\
&\quad - \dots \\
&\quad - [A_1 - E(A_1)] \cdot (TACC_1 + q_1) \cdot [T_n - E(T_n)] \cdot q_n \\
&\quad + [A_2 - E(A_2)] \cdot (TACC_2 + q_2) \cdot [A_1 - E(A_1)] \cdot (TACC_1 + q_1) \\
&\quad + \dots \\
&\quad + [A_2 - E(A_2)] \cdot (TACC_2 + q_2) \cdot [A_n - E(A_n)] \cdot (TACC_n + q_n)
\end{aligned}$$

$$\begin{aligned}
& - [A_2 - E(A_2)] \cdot (TACC_2 + q_2) \cdot [T_1 - E(T_1)] \cdot q_1 \\
& - \dots \\
& - [A_2 - E(A_2)] \cdot (TACC_2 + q_2) \cdot [T_n - E(T_n)] \cdot q_n \\
& + \dots \} \\
= & E \{ [A_1 - E(A_1)]^2 \cdot (TACC_1 + q_1)^2 + \dots + [A_n - E(A_n)]^2 \cdot (TACC_n + q_n)^2 \\
& + [T_1 - E(T_1)]^2 \cdot q_1^2 + \dots + [T_n - E(T_n)]^2 \cdot q_n^2 \\
& + 2[A_1 - E(A_1)] \cdot (TACC_1 + q_1) \cdot [A_2 - E(A_2)] \cdot (TACC_2 + q_2) \\
& + \dots \\
& + 2[A_1 - E(A_1)] \cdot (TACC_1 + q_1) \cdot [A_n - E(A_n)] \cdot (TACC_n + q_n) \\
& + 2[A_2 - E(A_2)] \cdot (TACC_2 + q_2) \cdot [A_3 - E(A_3)] \cdot (TACC_3 + q_3) \\
& + \dots \\
& + 2[A_2 - E(A_2)] \cdot (TACC_2 + q_2) \cdot [A_n - E(A_n)] \cdot (TACC_n + q_n) \\
& + \dots \\
& + 2[A_{n-1} - E(A_{n-1})] \cdot (TACC_{n-1} + q_{n-1}) \cdot [A_n - E(A_n)] \cdot (TACC_n + q_n) \\
& + 2[T_1 - E(T_1)] \cdot q_1 [T_2 - E(T_2)] \cdot q_2 \\
& + \dots \\
& + 2[T_1 - E(T_1)] \cdot q_n [T_n - E(T_n)] \cdot q_n \\
& + 2[T_2 - E(T_2)] \cdot q_2 [T_3 - E(T_3)] \cdot q_3 \\
& + \dots \\
& + 2[T_2 - E(T_2)] \cdot q_2 [T_n - E(T_n)] \cdot q_n \\
& + \dots \\
& + 2[T_{n-1} - E(T_{n-1})] \cdot q_{n-1} [T_n - E(T_n)] \cdot q_n \\
& - 2[A_1 - E(A_1)] \cdot (TACC_1 + q_1) [T_1 - E(T_1)] \cdot q_1 \\
& - \dots \\
& - 2[A_1 - E(A_1)] \cdot (TACC_1 + q_1) [T_n - E(T_n)] \cdot q_n \\
& - 2[A_2 - E(A_2)] \cdot (TACC_2 + q_2) [T_1 - E(T_1)] \cdot q_1 \\
& - \dots \\
& - 2[A_2 - E(A_2)] \cdot (TACC_2 + q_2) [T_n - E(T_n)] \cdot q_n \\
& - \dots \\
& - 2[A_n - E(A_n)] \cdot (TACC_n + q_n) [T_1 - E(T_1)] \cdot q_1 \\
& - \dots \\
& - 2[A_n - E(A_n)] \cdot (TACC_n + q_n) [T_n - E(T_n)] \cdot q_n \}
\end{aligned}$$

$$\begin{aligned}
&= E\{[A_1 - E(A_1)]^2\} \cdot (TACC_1 + q_1)^2 + \dots + E\{[A_n - E(A_n)]^2\} \cdot (TACC_n + q_n)^2 \\
&\quad + E\{[T_1 - E(T_1)]^2\} \cdot q_1^2 + \dots + E\{[T_n - E(T_n)]^2\} \cdot q_n^2 \\
&\quad + 2 E\{[A_1 - E(A_1)] \cdot [A_2 - E(A_2)]\} \cdot (TACC_1 + q_1) (TACC_2 + q_2) \\
&\quad + \dots \\
&\quad + 2 E\{[A_1 - E(A_1)] \cdot [A_n - E(A_n)]\} \cdot (TACC_1 + q_1) (TACC_n + q_n) \\
&\quad + 2 E\{[A_2 - E(A_2)] \cdot [A_3 - E(A_3)]\} \cdot (TACC_2 + q_2) (TACC_3 + q_3) \\
&\quad + \dots \\
&\quad + 2 E\{[A_2 - E(A_2)] \cdot [A_n - E(A_n)]\} \cdot (TACC_2 + q_2) (TACC_n + q_n) \\
&\quad + \dots \\
&\quad + 2 E\{[A_{n-1} - E(A_{n-1})] \cdot [A_n - E(A_n)]\} \cdot (TACC_{n-1} + q_{n-1}) (TACC_n + q_n) \\
&\quad + 2 E\{[T_1 - E(T_1)] \cdot [T_2 - E(T_2)]\} \cdot q_1 q_2 \\
&\quad + \dots \\
&\quad + 2 E\{[T_1 - E(T_1)] \cdot [T_n - E(T_n)]\} \cdot q_1 q_n \\
&\quad + 2 E\{[T_2 - E(T_2)] \cdot [T_3 - E(T_3)]\} \cdot q_2 q_3 \\
&\quad + \dots \\
&\quad + 2 E\{[T_2 - E(T_2)] \cdot [T_n - E(T_n)]\} \cdot q_2 q_n \\
&\quad + \dots \\
&\quad + 2 E\{[T_{n-1} - E(T_{n-1})] \cdot [T_n - E(T_n)]\} \cdot q_{n-1} q_n \\
&\quad - 2 E\{[A_1 - E(A_1)] \cdot [T_1 - E(T_1)]\} \cdot (TACC_1 + q_1) q_1 \\
&\quad - \dots \\
&\quad - 2 E\{[A_1 - E(A_1)] \cdot [T_n - E(T_n)]\} \cdot (TACC_1 + q_1) q_n \\
&\quad - 2 E\{[A_2 - E(A_2)] \cdot [T_1 - E(T_1)]\} \cdot (TACC_2 + q_2) q_1 \\
&\quad - \dots \\
&\quad - 2 E\{[A_2 - E(A_2)] \cdot [T_n - E(T_n)]\} \cdot (TACC_2 + q_2) q_n \\
&\quad - \dots \\
&\quad - 2 E\{[A_n - E(A_n)] \cdot [T_1 - E(T_1)]\} \cdot (TACC_n + q_n) q_1 \\
&\quad - \dots \\
&\quad - 2 E\{[A_n - E(A_n)] \cdot [T_n - E(T_n)]\} \cdot (TACC_n + q_n) q_n \\
&= Var(A_1) \cdot (TACC_1 + q_1)^2 + \dots + Var(A_n) \cdot (TACC_n + q_n)^2 \\
&\quad + Var(T_1) \cdot q_1^2 + \dots + Var(T_n) \cdot q_n^2
\end{aligned}$$

$$\begin{aligned}
& + 2 \operatorname{cov}(A_1, A_2) \cdot (TACC_1 + q_1) (TACC_2 + q_2) \\
& + \dots \\
& + 2 \operatorname{cov}(A_1, A_n) \cdot (TACC_1 + q_1) (TACC_n + q_n) \\
& + 2 \operatorname{cov}(A_2, A_3) \cdot (TACC_2 + q_2) (TACC_3 + q_3) \\
& + \dots \\
& + 2 \operatorname{cov}(A_2, A_n) \cdot (TACC_2 + q_2) (TACC_n + q_n) \\
& + \dots \\
& + 2 \operatorname{cov}(A_{n-1}, A_n) \cdot (TACC_{n-1} + q_{n-1}) (TACC_n + q_n) \\
& \\
& + 2 \operatorname{cov}(T_1, T_2) \cdot q_1 q_2 \\
& + \dots \\
& + 2 \operatorname{cov}(T_1, T_n) \cdot q_1 q_n \\
& + 2 \operatorname{cov}(T_2, T_3) \cdot q_2 q_3 \\
& + \dots \\
& + 2 \operatorname{cov}(T_2, T_n) \cdot q_2 q_n \\
& + \dots \\
& + 2 \operatorname{cov}(T_{n-1}, T_n) \cdot q_{n-1} q_n \\
& \\
& - 2 \operatorname{cov}(A_1, T_1) \cdot (TACC_1 + q_1) q_1 \\
& - \dots \\
& - 2 \operatorname{cov}(A_1, T_n) \cdot (TACC_1 + q_1) q_n \\
& - 2 \operatorname{cov}(A_2, T_1) \cdot (TACC_2 + q_2) q_1 \\
& - \dots \\
& - 2 \operatorname{cov}(A_2, T_n) \cdot (TACC_2 + q_2) q_n \\
& - \dots \\
& - 2 \operatorname{cov}(A_n, T_1) \cdot (TACC_n + q_n) q_1 \\
& - \dots \\
& - 2 \operatorname{cov}(A_n, T_n) \cdot (TACC_n + q_n) q_n \\
& \\
& = \sum_{i=1}^n \sum_{j=1}^n (TACC_i + q_i) (TACC_j + q_j) \sigma_{ij} + \sum_{i=1}^n \sum_{j=1}^n q_i q_j v_{ij} - 2 \sum_{i=1}^n \sum_{j=1}^n (TACC_i + q_i) q_j \omega_{ij},
\end{aligned}$$

where σ_{ij} denotes the covariance between A_i and A_j , v_{ij} denotes the covariance between T_i and T_j , ω_{ij} denotes the covariance between A_i and T_i .

Appendix 2

Species List

1. Hoki (HOK)
2. Red rock lobster (CRA)
3. Paua (PAU)
4. Arrow squid (SQU)
5. Orange roughy (ORH)
6. Snapper (SNA)
7. Ling (LIN)
8. Hake (HAK)
9. Scampi (SCI)
10. Tarakihi (TAR)
11. Alfonsino (BYX)
12. Barracouta (BAR)
13. Black cardinalfish (CDL)
14. Blue cod (BCO)
15. Blue moki (MOK)
16. Blue shark (BWS)
17. Blue warehou (WAR)
18. Bluenose (BNS)
19. Cockle (COC)
20. Elephant fish (ELE)
21. Flatfish (FLA)
22. Gemfish (SKI)
23. Grey mullet (GMU)
24. Jack mackerel (JMA)
25. John dory (JDO)
26. Kahawai (KAH)
27. Mako shark (MAK)
28. Orange roughy (ORH)
29. Oreo (black) (OEO (BOE))
30. Oreo (smooth) (OEO (SSO))