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Working Paper Series

Working Paper 15-WP-SEMRU-01

The species targeting responses of fishers to single species quota changes in a multispecies fishery

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Abstract

In fisheries characterised by multiple target species, and in particular those with joint harvesting technologies, managers can inadvertently impact numerous species under management by way of single species focused regulatory measures. By curtailing the capacity of fishers to attain revenues from a particular species, effort is displaced and often directed towards alternative species. Treating fishers as utility maximising agents, in which utility (and thus species targeting effort) is positively associated with expected revenue and negatively associated with revenue variability, this paper employs portfolio theory to analyse fishers' species targeting choices in the Irish Hake-Monkfish-Megrim and Cod-Haddock-Whiting fisheries. The particular concern is adjustments to targeting decisions when species-specific quota constraints are implemented. The analysis uses the utility maximising assumption in a mean variance optimisation framework to approximate fishers' objective function. Species targeting behavioural changes, identified as changes in the species composition of fishers' optimal harvest portfolio, suggest significant displacement of fleet into alternative fisheries occurs when barriers to such alternation do not exist.

Keywords: multispecies fisheries management, portfolio theory, behavioural economics.

This work was funded through the Beaufort Marine Research Award, which is carried out under the *Sea Change* Strategy and the Strategy for Science Technology and Innovation (2006-2013), with the support of the Marine Institute, funded under the Marine Research Sub-Programme of the National Development Plan 2007–2013.

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1. Introduction

A new and reformed European Common Fisheries policy (CFP) began implementation across all EU marine waters in January 2014. One outcome of the agreements is that quotas and the use of species' maximum sustainable yields (MSY) will remain the primary means by which Member States (MS) attempt to achieve sustainable fisheries. Political problems with this form of fisheries management and with maintaining the scientifically recommended MSY throughout the political process have been documented within the EU (Daw and Gray, 2004). Despite these highlighted problems, the reforms indicate that the degree to which scientific recommendations of MSY are adhered to in practice will be far more binding than has been the case historically, such that by 2020, all stocks are to be managed at MSY. It is now clear that major changes to fishing quotas in European waters will occur in the next 6 years.

Further changes to the CFP include a banning of all discards and the adoption of multi-annual and multi-species planning. This means that the quantity of any fish stock that can be sustainably harvested will be determined on the basis of interaction with, and impacts upon, other species and marine habitats. If sustainable fisheries are to be attained, the impact of fishing for a single commercial species on other commercial species will be of great importance. It is foreseeable that in waters where the by-catch of biologically sensitive species is high, quotas for any target species in question will be set lower than their potential MSY level (had they been considered in isolation).

According to the European Commission, EU legislators will only define the general framework, the basic principles and standards and the overall targets of the CFP while Member States will themselves develop recommendations on the actual implementing measures (EC, 2013). National policy makers will thus be charged with the responsibility of deciding upon and implementing the medium term management initiatives that will achieve the overall targets of the CFP. In this new policy environment, when settings species' total allowable catches (TACs), fishery managers must pay particular attention to the multispecies impact of harvesting an individual species, not least, the impact on other commercial species within the fishery and in neighbouring fisheries.

Models assisting the management process that follows the reforms will need to assess the environmental and ecosystem impacts of commercial fishing activity. In addition, behavioural economic models have a role to play since they offer a framework for attempting to describe the response of fishermen to any policy changes. According to Fulton et al (2011), human behaviour, and in particular fisher behaviour, is almost never explicitly considered by fisheries scientists in the assessment and management process. They posit that the uncertainty generated by unexpected resource user behaviour is as critical as ecosystem and environmental uncertainty because it has unplanned consequences and leads to unintended management outcomes. Indeed, technical measures can lead to results which actually work directly against specific sustainability targets for which they are designed (Briand et al., 2004; Rijnsdorp et al., 2001; Dinmore et al., 2003; White and Mace, 1988; Kolody et al., 2008; Polacheck and Davies, 2008).

While behavioural models may be under utilised by fisheries scientists, empirical analyses on the socio-economic impacts of fisheries regulations are plentiful (e.g. Jentoft, 2000; Nielsen, 2003; Hatcher and Pascoe, 2006; Wislon et al., 2006). Given the recent EU policy developments prioritising the by-catch issue and multispecies management, empirical analyses that have the potential for multispecies level analyses are desirable. This article presents a behavioural modelling approach based on financial portfolio theory and the expected utility hypothesis in an attempt to model the change in the harvest behaviour of a fishing fleet affected by precautionary quota constraints. The intent of the research is to demonstrate how the portfolio methodology could be employed by fishery managers to predict the likely behavioural responses of a fishing fleet to changing quota restrictions. While this process is useful in its own right, it also demonstrates the need for improved fishery data collection processes to implement such models successfully. The portfolio approach is based on the portfolio theory developed by Markowitz (1952). Markowitz's portfolio analysis is a mathematical tool to determine how to select the optimum proportion of assets in a portfolio for investment. The approach lends itself well to multispecies fishery analysis because given certain assumptions about the objective function of a fishing fleet it is possible to estimate changes in multispecies targeting behaviour given changes in single species harvest constraints. Thus a "multi-species-wide" impact of precautionary measures can be assessed. While portfolio theory has been extensively used for research into financial, agricultural and energy markets, its application to fisheries management and policy is rare. Some of the few papers that have done so are reviewed in the following section.

Section 2 discusses previous literature that applies portfolio theory to fishery economic issues. Section 3 then presents the theory underlying the portfolio approach and how it is applied in this study to the concept of mixed fisheries management. Section 4 provides a description of the multispecies Irish fishery investigated in the analysis and a brief description of the data used. The estimation results of alternative management scenarios are then presented in section 5. The paper concludes with a discussion of its major findings and their implications for fisheries management.

2. Previous applications of portfolio theory within fisheries economics

While portfolio theory has been routinely applied in agricultural economics (e.g. Kelley et al., 2013), empirical multi-species analysis usually follows one of two formats; a bio-economic model which determines the optimal harvest rate of more than one species using estimated predator-prey or competitor parameters, or structural ecosystem models that can be used to determine optimal TACs across multiple species. More recently however, portfolio theory has been applied to ecosystem management (Breen and Hynes, 2014), and more specifically, fisheries management, due to its capacity to embody a multi-species perspective and directly incorporate risk. Hanna (1998) advocates portfolio theory as a means of balancing fisher objectives and societal objectives while others extend this idea to ‘explicitly recognize fishery resources as risk-bearing capital assets that can provide society with benefits indefinitely’ (Edwards et al., 2004; 2005). These studies focus on realigning the goals of individual fishers with societal goals by adopting property rights, incentive schemes and fishing restrictions such that ecosystem service payoffs (as opposed to commodity payoffs) can be delivered to society. Others see the portfolio approach as a means of protecting fishing communities from the risk of fluctuations in the abundance, availability, or price of individual species, where fishers choose among a diverse portfolio of harvestable resources rather than being forced by regulation to specialize in one or an extremely limited number of species (Hillborn et al. 2001).

Elsewhere, Yang et al. (2008) use portfolio theory to assess the behaviour of New Zealand fishers’ who face multiple targeting options to predict the optimal targeting strategies under a Quota Management System (QMS). Species considered by Yang, et al.(2008) were selected based on two criteria; the commercial value of the species and the availability of data. These two criteria were also highly relevant in this analysis of the Irish mixed fisheries and will be discussed further in section 3.

Sanchirico, Smith and Lipton (2006) also adapted financial portfolio theory as a method for ecosystem based fishery management (EBFM) that accounts for species interdependencies, uncertainty, and sustainability constraints. Illustrating the method with routinely collected species catch data available from Chesapeake Bay in the United States, the authors demonstrate the gains from taking into account species variances and covariances in setting species total allowable catches. They find over the period from 1962–2003 that managers could have increased the revenues from fishing and reduced the variance by employing ecosystem frontiers in setting catch levels. Sanchirico, Smith and Lipton (2006) also point out that compared to structural models of the ecosystem, deriving ecosystem frontiers provides a complementary view that is simple to implement and flexible enough to accommodate different ecological, economic, and social objectives by including additional constraints or objective functions. However, they also point out that a limitation of ecosystem frontiers is that the policy prescriptions are only as good as the estimates of the means and covariances that characterize the multivariate stochastic process.

Elsewhere, Perusso et al. (2005) highlight the fact that fisheries regulations tend to be species specific but that species can be part of a multi-species fishery. Therefore since harvest rates are correlated, net revenues attributed to each species are also likely to be correlated. The authors contend that this correlation means that portfolio theory is well suited for multi-species fisheries that exhibit joint productive characteristics. The authors therefore used a portfolio approach to model the behaviour of fishermen faced with multiple targeting options in a random harvest fishery. The approach draws from the expected utility hypothesis and financial portfolio theory to predict optimal targeting strategies. The methodology was applied to the pelagic long line fleet operating in the U.S. Atlantic Ocean, Caribbean and Gulf of Mexico. Results from the model provide evidence that area closures aimed at reducing juvenile swordfish mortality will be more effective in certain regions. Efficient risk-return frontiers were also generated for use in predicting targeting behaviour in lieu of a closure. The frontiers suggested that trips that target swordfish exhibit a smaller degree of variability than trips that do not.

More recently, Theophille (2012) uses a mean-variance portfolio optimization approach to determine whether there is potential for fishers in Dominica to reduce the variability of net trip revenues. Their results suggested that fishers could attain their ex ante targets and that given the potential for trip-level harvest portfolios with a more efficient mean-variance profile, the variability of net trip revenues could be reduced.
We employ portfolio theory to combine a multispecies and precautionary approach under a single empirical framework and follow Perusso et al. (2005) by incorporating the expected utility hypothesis into the analysis. Through this approach, an attempt is made to predict the impact of hypothetical quota-based precautionary measures on the utility of fishermen in the Hake-Monkfish-Megrim and the Cod-Haddock-Whiting fisheries in Irish waters. To infer realistic hypothetical precautionary measures reference is made to Cawley et al. (2006) in which the authors therein review the status of various Irish fish species and the potential measures that need to be adopted to protect specific stocks from decline. The behavioural response of the fleet to precautionary measures is assessed by observing the subsequent changes in the contribution of target species to the overall fisheries harvest portfolio. This contribution is often referred to as the, portfolio "weight", of a particular species. This approach is novel in that both the portfolio theory and expected utility frameworks are combined to address the topic of species-specific quota restrictions using precautionary TACs produced by practising Irish fisheries scientists.

3. Methodology

Portfolio theory assumes that economic agents are profit maximizing and risk averse, balancing a range of expected payoffs (and the risk/variability associated with attainment of each payoff) to maximize their expected utility. The portfolio problem is thus formulated using the expected utility function of Von Neuman-Morgenstern (1944) and can be written:

$$\underset{x_1,\dots,x_N}{max} E[U(W_1)] = E\{\ U \left[\left(1+\sum_{i=1}^{N} x_i R_i) \ W_0 \right\}\right]\} \tag{1}$$

where $\mathrm{E}(.)$ is the expected value of $(.)$, U is utility level, W_0 and W_1 are initial and updated wealth respectively, R_i is the return on the ith asset and x_i is the percentage contribution of the ith asset to the total harvest portfolio. In this study, it is assumed that the fishery manager looks at the fleet as a single entity, forming expectations about the revenue it can generate from harvesting each of a set of species and the risk (variability) associated with each revenue stream. It then uses these expectations to select the portfolio of target species that maximises its expected utility. As in other examples (Mistaien and Strand, 2000; Perusso et al. 2005) it is assumed that the fleet's initial wealth is zero so that the possibility of existing wealth influencing ex ante targeting decisions does not arise. Furthermore, due to the absence of cost data, the focus is on the impact of fishery revenues on fleet utility as opposed to the more ideal case of the impact of fishery returns on fleet utility. This means that the main determinants of the fleets targeting decisions arise out of annual revenues. Like Perusso et al. (2005), a Taylor Series expansion is used to approximate the utility function, but because this study only has annual and aggregated level data available, this is done for annual revenues $E[W^*]$ for the entire fleet as a unit:

$$U(W^*) = U(E[W^*]) + U'(E[W^*])(W^* - E[W^*]) + \frac{1}{2}U''(E[W^*])(W^* - E[W^*])^2 + R_3 \tag{2}$$

where:

$$R_3 = \sum_{n=3}^{\infty} \frac{1}{n!} U^{(n)}(E[W^*])(W^* - E[W^*])^n, \tag{3}$$

U^n is the n-th derivative of U and $\mathrm{E}[.]$ is the expected value of $[.]$. A convergent Taylor series leads to total fleet expected utility,

$$E[U(W^*)] = U(E[W^*]) + \frac{1}{2}U''(E[W^*])\sigma^2(W^*) + E[R_3]. \tag{4}$$

where $\sigma^2(W^*)$ is the variance of annual fleet revenue . And:

$$E[R_3] = \sum_{n=3}^{\infty} \frac{1}{n!} U^{(n)}(E[W^*])m^n(W^*). \tag{5}$$

where $m^n(W^*)$ is the n-th central moment of W^*:

As per Perusso et al. (2005), this latter equation reflects the fact that expected utility is explained by mean, variance and other high moments of the probability distribution of fleet revenue. Ideally, the availability of cost data would allow the researcher to model expectations about returns/profit. This would allow the model to more accurately reflect the feasibility of alternative combinations of aggregate catch within the fishery. In the absence of such cost data, one can still apply the methodology to fisheries in cases such as ours where the fisheries being investigated are assumed to have equivalent fixed costs (such that there are no barriers to exit one fishery and enter another) and similar variable costs structures. This is discussed in more detail in section 5. It would also be superior to have more frequently observed data on catch quantities and prices since variance in annual total revenue over time is unlikely to be randomly or independently distributed. A further issue with the data is that it contains observations of only the Irish fleet's revenues and thus the variability of revenue experienced by other fleets is omitted, so that the actual variance of annual revenues may differ to the figure produced by the model. These shortcomings mean that for a set of harvest targets one cannot be sure that the distribution of expected catch around those targets will be accurately represented by the variance of revenues from earlier years. With that said, the purpose of applying a portfolio model in this case is to demonstrate how the framework could be employed by managers of a multispecies fishery and the types of data that would be needed to do this successfully.

As earlier stated, the expected utility of the fleet is a function of the mean and variance of revenue:

$$\mathrm{E}(\mathrm{U}_i) = \mathrm{E}(\mathrm{R}_i) - \varphi(\sigma_i^2) \tag{6}$$

where $\mathrm{E}(.)$ is the expected value of $(.)$, U is the fleet's utility, R_i is revenue per tonne of species i harvested, φ is the fleets risk aversion parameter and is the same toward all species, and σ_i^2 is the variance the fisher expects from the revenue generated from harvesting species i, defined as the variance in average revenue per tonne of species i harvested over the historical period.

Correspondingly, the expected utility of the fleet, written now as a function of the first two moments of the *harvest portfolio* $\emptyset$, is

$$E(U_{\emptyset}) = E(R_{\emptyset}) - \varphi\left(\sigma^{2}_{\emptyset}\right) \tag{7}$$

where:

$$R_{\emptyset} = \sum_{i=1}^{n} w_i R_i \tag{8}$$

$$R_i = P_i Y_i \tag{9}$$

and $\sum w_i \leq \sum i$ i.e. $0 \leq w_i \leq 1$; $w_i R_i \geq 0$; $Y_i \geq 0$; $P_i > 0$. P_i is the unit price of species i, Y_i is the tonnage of species i harvested and w_i is the weighting on species i in the harvest portfolio. Note that each weight on each species can equal 1 simultaneously since the specification relates using expected revenues rather than expected returns. To elaborate, the emphasis is not on returns, which are fractional (meaning all weights should sum to 1) but are instead talking about revenues (which are not fractional), meaning the sum of the weights can sum to whatever amount of species exist in the harvest portfolio. The expected revenue for any fleet harvest portfolio $\emptyset$ then, is simply the sum of the expected revenues by the weight allocated to each species in the fleet harvest portfolio. Note that the weight allocated to each species is the percentage share of total catch. For risk however, one must also consider the covariance between the revenues generated from harvesting each species. Such covariance arises out of ecosystem linkages such as a predator-prey or competitor relationships (Garrod and Harding 1981; Daan, Rijnsdorp and Overbeeke 1985; Daan 1989; Köster and Schnack 1994, Trenkel et al. 2004), common sensitivity (be it positive or negative) to environmental fluctuations and fishing types, and indeed, any macro type variable that affects multiple species within the ecosystem, or in this case, the harvest portfolio, $\emptyset$. As earlier alluded to, out annual measures of price and quantity are quite crude compared to the level of detailed data required to get at the true distribution of expected revenues fishermen perceive in achieving their target harvests. However they allow us to carry out the methodology and demonstrate its potential should more quality data be available.

Price sensitivities to market conditions also cause covariance between revenues. Calculations of revenue covariances capture this, but here Sanchirico et al. (2006) is followed in assuming that fish prices are unresponsive to ecosystem-wide catch levels due to substitute protein sources and world seafood markets. This means that the degree of price substitution or complementariness between species in the portfolio is irrelevant compared to other market factors, and therefore prices can be classified as exogenous[i]. As demonstrated by Sanchirico et al. (2006), the technique of exponential smoothing is employed, meaning the less recent an observation of P_i and Y_i, the less influence it has in the calculation of $E(R_{\emptyset})$ and $\sigma_{\emptyset}^2$. The degree to which the influence of past observations on expected values diminishes is determined by a factor referred to as the rate of decay (λ). This technique allows us to mimic the possibility that fishers place more emphasis on recently occurring events when forming expectations about future outcomes (Guttormsen 1999; Bowerman and O'Connell 1993), but one can also relax this assumption by increasing the value of λ until such a point as it reaches 1, whereby all observations, regardless of the time period in which they occur, are equally weighted. Each term in the variance covariance matrix of the fleet's harvest portfolio is then calculated as:

$$\sigma_{ij} = \frac{\sum_{k=0}^{t-1}\lambda^{t-k}((R_{j,t-k})-E(R_j))^2}{\sum_{k=0}^{t-1}\lambda^{t-k}} \tag{10}$$

Where:

$$R_t = \frac{\sum_{k=0}^{t-1}\lambda^{t-k}(R_{j,t-k})^2}{\sum_{k=0}^{t-1}\lambda^{t-k}} \tag{11}$$

Note that the definition of R_i is the same as before (P_iY_i), only now the observation from each time period is weighted in relevance according to the decay factor λ. The total variance $\sigma_{\emptyset}^2$ of the fleet harvest portfolio is then defined:

$$\sigma_{\emptyset}^2 = \sum_{i=1}^{n}\sum_{j=1}^{n}\sigma_{ij}w_iw_j = \rho_{ij}\sigma_i\sigma_jw_iw_j \tag{12}$$

where σ_i is the standard deviation of R_i, σ_{ij} is the covariance in revenue between species i and j, except when $i = j$ (meaning σ_{ii}), at which point it refers to the *variance* of R_i, that is, σ_i^2. ρ_{ij} is the correlation coefficient between the revenues for i and j and when $i = j$, it must be equal to 1.

With the definitions of the different variables in place, the quadratic programming problem is then:

$$\text{Minimize } \sigma_{\emptyset}^{2} = \sum_{i=1}^{n}\sum_{j=1}^{n} \sigma_{ij} w_i w_j \tag{13}$$

subject to:

$$R_{\emptyset} = \sum_{i=1}^{n} w_i R_i \geq T_{\emptyset},\ w_i Y_i \leq PL_i \tag{14}$$

where $T_{\emptyset}$ is some target level of revenue for fleet harvest portfolio $\emptyset$, and PL_i is a precautionary catch limit set by management for species i (specifically it is a species weight constraint within the harvest portfolio). By carrying out the optimization procedure for increasing values of $T_{\emptyset}$ (starting from zero) the minimum level of $\sigma_{\emptyset}^{2}$ for each value of $R_{\emptyset}$ is calculated. Plotting the different values of $\sigma_{\emptyset}^{2}$ for every value of $R_{\emptyset}$ produces what is termed, the efficient frontier of the entire fleet[ii].

In this case, the efficient frontier represents the minimum expected variance the fleet can achieve on the basis of historical covariances in order to attain its target expected revenue. Or perhaps more accurately how fishery managers will expect the fleet to behave given historical outcomes. The final determinant of the fleet's target level of revenue, given the expected variance associated with it, will be the aggregated attitude of all fishers within the fishery towards risk, represented through the risk aversion parameter φ, and this in turn will determine the weight allocated to each species within the fleet's portfolio; it is by adjusting the species weights (either through the fleets own decision making or through management determined quotas) that the fleet target portfolio travels along the efficient frontier. Once a target level of revenue is set, the harvest portfolio associated with it is delineated by directing fishing effort into achieving the weights that will determine such a portfolio's expected revenue and variance. There is a depiction of the relationship between the efficient frontier, aversion to risk, and the expected utility curve in Fig. 1. Fleet 1 has a high aversion to risk, and therefore selects a mix of species which result in low revenue, but a correspondingly low expected variance (expected utility curve 1). Fleet 2 is at the opposite end of the scale and is less risk averse and selects the mix of species which achieve higher expected revenue but expose the fleet to a higher level of variance (expected utility curve 3). This study assumes the Irish fishing fleet to have a risk aversion parameter φ, of 1, to allow for brevity in the analysis, but it is possible to adjust this for other analyses so that a more risk loving (or risk averse) fleet can be considered.

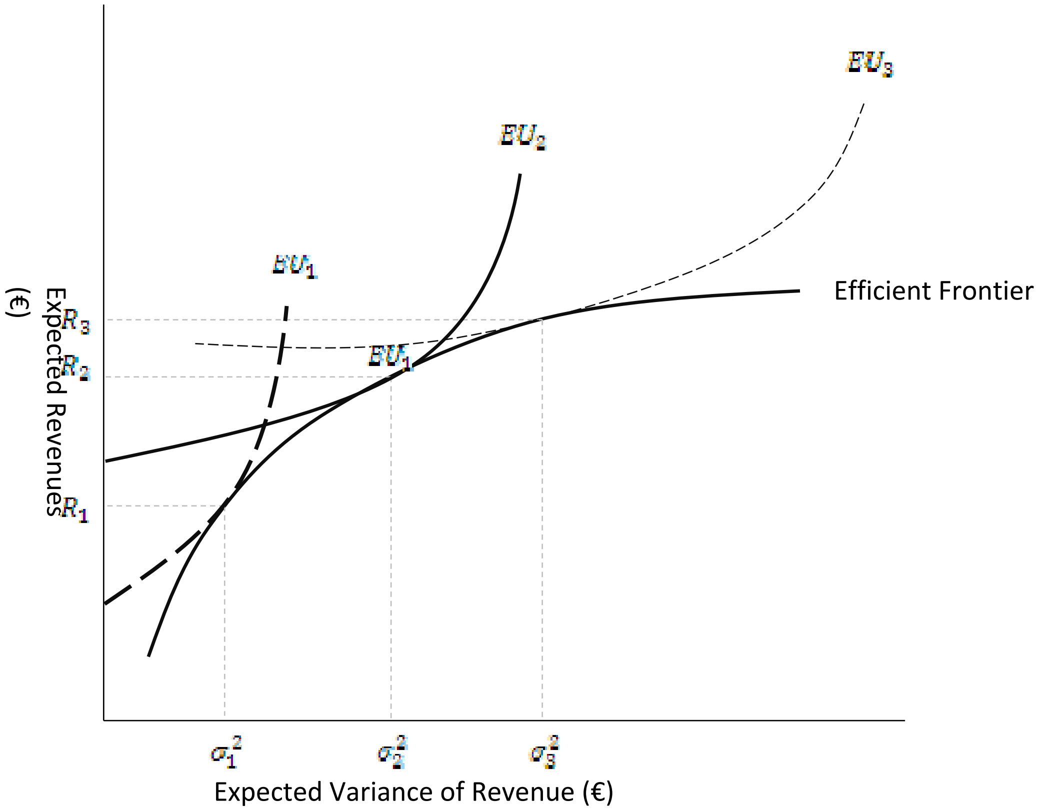

Fig 1: Hypothetical efficient frontier and expected utility curve of three different individuals, each with a differing aversion toward risk

4. Data and the Irish Mixed Species Fisheries

The seas around Ireland contain some of Europe's most important fishing grounds. Irish-Atlantic coastal waters, the West of Scotland coast and Rockall, the Celtic Sea and the Irish Sea possess a rich abundance of commercially fished species and diverse marine habitats which support them. According to statistics from the Irish Sea Fisheries Protection Authority, the total value of fish landings in the Irish fisheries sector in 2008 amounted to €214 million (SFPA 2010). Comprising 16% of total EU waters (Irish Naval Service 2007), Irish territorial waters are currently governed as part of the European Union's Common Fisheries Policy (CFP). The reform of the CFP in 1983 established the concepts of Exclusive Economic Zones (EEZs)[iii] within EU waters, relative stability[iv] and conservatory management measures based on TACs[v].

The quantities of fish caught in EU waters today are therefore regulated by determining the annual TAC of each commercially fished species through scientific advice and a political process established under the CFP. Member states are then allocated a share/quota of this TAC on a fixed percentage basis, determined largely by their historical fishing patterns and relative dependency on the fishing industry.

The Irish fish catching sector is largely comprised of deep water, demersal, pelagic and shellfish fisheries (see Table 1 for a breakdown of Irish fishing segments and relevant target species).

Table 1. Irish species pertaining to each segment of the Irish Fishery

Segment	Targeted Species
Pelagic	Pelagic species: Mackerel, Herring, Horse Mackerel, Blue Whiting, Sprat, Sardines
Polyvalent	Whitefish Species: Monkfish, Megrim, Haddock, Whiting, Cod, etc. Dublin Bay Prawns/Nephrops, Pelagic Species (limited quantity). Inshore Non-Quota Shellfish Stocks
Beam-trawl	Flatfish species: Sole, Plaice, Megrim, Monkfish
Specific	Bivalve Molluscs: e.g. Mussels, Scallop, Razor clams

Our analysis focuses on, firstly, the Hake, Monkfish and Megrim fishery and secondly on the Cod, Haddock and Whiting fishery. This is because these fisheries are multi-species in nature and therefore the type of fisheries where cross-species effects of single species quota constraints occur, making them suitable for an application of the portfolio approach. They are also fisheries in which substantial species interrelatedness is documented in the scientific literature (Hislop 1996; Garrod and Harding 1981; Daan et al.1985; Daan 1989; Köster and Schnack 1994; Bromley et al. 1995; Trenkel et al. 2004). Given the extent of species interrelatedness that exists for the fisheries under study, a portfolio theory approach, which estimates a variance covariance matrix across species catch quantities seems a viable approach to incorporating species interdependency.

Ireland’s quota for the Hake Monkfish and Megrim fishery comprises 9% of the EU TAC. The fishery generated €18.9m in dockside revenue in 2004 and accounted for 29% of demersal landings. Both Hake and Monkfish can be targeted using either longline, trawl or gillnet methods and are therefore core target species of the polyvalent and beam trawl segments of the Irish fishing fleet. Megrim is largely caught using trawling methods. While the beam trawl segment comprises only 1% of the vessels in the Irish fleet and 2% of the capacity, the polyvalent segment represents 85% of the fleet and 48% of capacity (Cawley et al.et al. 2006). In recent years, the Irish quota for Hake and Monkfish has increased by 12% and 30% respectively yet Cawley et al. (2006) point out that recent ICES advice suggested Monkfish was ‘over-exploited in relation to its highest yield’.

The Cod, Haddock and Whiting fishery have also experienced declining stocks in recent years. Indeed there has been a dramatic decline of Cod in all the main fisheries around Ireland and in the North Sea (Cawley et al. 2006). Ireland’s quota of Cod, Haddock and Whiting amounts to 17% of the TAC and the first point of sale value was €12.1 million in 2004. Landings of Cod, Haddock and Whiting accounted for 18% of the total value of demersal species landed in 2004, contrasting starkly with a 26% contribution in 1995. According to Cawley et al. (2006), this had led to ‘significant displacement of traditional fleets from these areas and today many of the larger vessels from the Greencastle fleet travel regularly to the Celtic Sea to fish. Likewise the traditional Irish Sea whitefish fleet has all but disappeared. It is clear too that as more vessels turn their attention to the Hake, Monkfish and Megrim fishery in the Celtic Sea and to the Dublin Bay prawn fisheries both in the Irish Sea and off the south-west coast, these already heavily fished stocks are very vulnerable to further over-exploitation (Cawley et al.2006). More recently, the Irish stock book (2011) finds that Cod and Whiting are overly exploited and severely depleted in the Irish Sea. In the Celtic Sea surveys revealed a downward trend in the biomass and abundance of cod, whiting and hake. Recent dedicated anglerfish/monkfish surveys indicate a decline in abundance since 2007.

The historical price and quantity data used in the analysis is collected by the Sea Fisheries Protection Authority (SFPA) and reported annually by the Irish Central Statistics Office (CSO). The SFPA collects and analyses data on fish landings and

fishing activity by all Irish vessels and foreign vessels landing into Ireland. This data includes information on the quantity, value, and location of fish caught, together with effort data and details of fishing methods used. Fish and shellfish are landed at the five major fishery harbour centres (Killybegs, Castletownbere, Howth, Rossaveal, and Dunmore East), at 40 secondary ports (each with landings exceeding €1m) and a further 80 piers and landing places across Ireland (Cawley et al.2006). The revenue R_{it} generated by each species in each year is calculated using the total quantity Y_{it} of each species i recorded/landed at all of the main ports around Ireland in that year, and the average dockside price P_{it} of each species for all of the ports during the year.
The sample period used in the analysis is 1977 until 2004. While data for years earlier than this is available from the CSO for the Cod, Haddock and Whiting fishery, it is not available for the Hake, Monkfish and Megrim fishery. The principal variables reported by the CSO for Irish fisheries are species class, aggregate landings by port/consumption category/month/average live weight per tonne and value by main species. While individual vessel level data would be more useful for an in-depth economic analysis of each fishery, the portfolio approach lends itself well to the analysis of aggregate price and quantity data, such as that collected by the CSO in this case.

5. Results

The portfolio theory approach is used to consider three different fishery management scenarios. In the first scenario the status quo situation in each fishery is looked at. This is specified as the catch composition of the most recently observed harvest portfolio (2004). This is then compared to the optimal portfolio the fleet could have attained based on historical revenues and covariances. This indicates the accuracy of the model's predictions about the fisheries' targeting choices as a whole and the extent of any risk-revenue balancing behaviour the fleet potentially engages in.

In the second scenario, a hypothetical precautionary quota constraint for a single species is replicated so as to observe how the fleet's targeting behaviour toward alternative species in the *same* fishery changes. Sticking with this hypothetical case (the second scenario), the precautionary measure is replicated a second time but the fleet is permitted to switch its targeting effort to species in the neighbouring fishery also. Fisheries are specifically selected according to the extent of ecosystem linkages (Garrod and Harding 1981; Daan, Rijnsdorp and Overbeeke 1985; Daan 1989; Köster and Schnack 1994, Trenkel et al. 2004) and in the sense that the multiple species which make up the two fisheries are genuine harvest alternatives to each other. This is because fishers within each fleet can alternate targeting behaviour to the other fishery without having to incur any substantial fixed costs since both fisheries fall into the demersal and seine trawlers category.

If alternating between the fisheries in question required vessels to undergo costly gear and equipment changes, fixed costs would be far more important in the analysis since fixed costs act as a barrier to entering a new fishery. Allowing for species harvesting alternatives in the modelling process that are not realistic in practice (due to fixed costs barriers to entry) could lead to erroneous results if fixed data was not included in the model. This study would benefit from having variable cost data, however this data is not available at this time and by selecting fisheries that had only marginally different variable costs, the implication of omitting costs from the analysis was minimised. The similarity in variable costs between the two fisheries is highlighted by the fact that data on the cost structures of these two fisheries are aggregated in Bord Iascaigh Mharra (Irish Sea Fisheries Board) annual economic fishery surveys.

In the third scenario, a second precautionary quota constraint, placed on a different species in the neighbouring fishery, is hypothesised. The intention is to mimic a situation where the initial precautionary initiative forces displaced fishing effort into the alternative fishery, increasing the fishing pressure on its stocks, causing management to respond by implementing a second quota constraint in the affected fishery. The results and implications of the various outcomes are then discussed, both for the fisheries in question, and the fisheries portfolio methodology itself.

Table 2 below presents the descriptive statistics for the species in each of the two fisheries for different values of the decay factor λ. The expected revenue values have the property of non-monotonicity as the value of λ changes. This arises because the historical price and quantity of each species varies across time, and different values of λ weight different time periods differently. Where the expected revenue value is highest when $\lambda=0.741$ it is likely that the species was under-exploited in the earlier portion of the sample period, became increasingly exploited in the middle period, and then due to overfishing suffered decline. The result shows the benefit of using a decay factor to describe fishers' expectations since it reflects a more accurate depiction of "current" opportunities in the fishery. Throughout this analysis, a λ of .549 is assumed, meaning that only 5% of the weight of an observation in calculating expected values remains after five years. Table 3 presents the correlation matrix of all potential species in the fisheries' harvest portfolios. The correlation coefficients range from less than 1 to negative values suggesting that there *is* scope for risk diversification in the fishery.

Table 2. Descriptive Statistics for Species Revenues (Euros) for different λ

	Average Revenue			St. Dev		
λ	1	0.741	0.549	1	0.741	0.549
Cod	10,971,720	7,131,533	5,649,362	3,041,685	2,870,629	1,972,226
Haddock	4,945,147	6,390,685	5,800,260	2,262,687	1,884,751	1,575,015
Whiting	8,088,805	6,685,095	5,583,926	1,947,514	2,268,947	1,812,277
Hake	5,988,474	5,376,045	4,164,673	3,782,108	2,618,039	1,630,326
Monkfish	6,602,780	10,021,560	9,739,959	4,280,490	1,358,567	1,069,687
Megrim	8,079,675	10,031,690	8,794,949	4,893,231	2,992,306	2,434,117

Table 3. Variance-covariance matrix of specie revenues (Euros) for λ=1

	Cod	**Haddock**	**Whiting**	**Hake**	**Monkfish**	**Megrim**
Cod	1					
Haddock	-0.091	1				
Whiting	0.509	0.023	1			
Hake	0.197	0.495	-0.01	1		
Monkfish	-0.207	0.721	-0.081	0.764	1	
Megrim	0.051	0.747	-0.023	0.829	0.876	1

Scenario 1: The Status Quo Situation

The Hake, Monkfish and Megrim fishery generated €20.53m in real dockside revenues in 2004. To attain this €20.53m in revenue, Irish fishers within the fishery selected a harvest portfolio with a standard deviation of €4.57m (based on the estimated variance/covariance matrix). By determining species weights optimally, it is estimated that the fleet could have achieved that same level of revenue by selecting a harvest portfolio with a standard deviation of €4.196m.

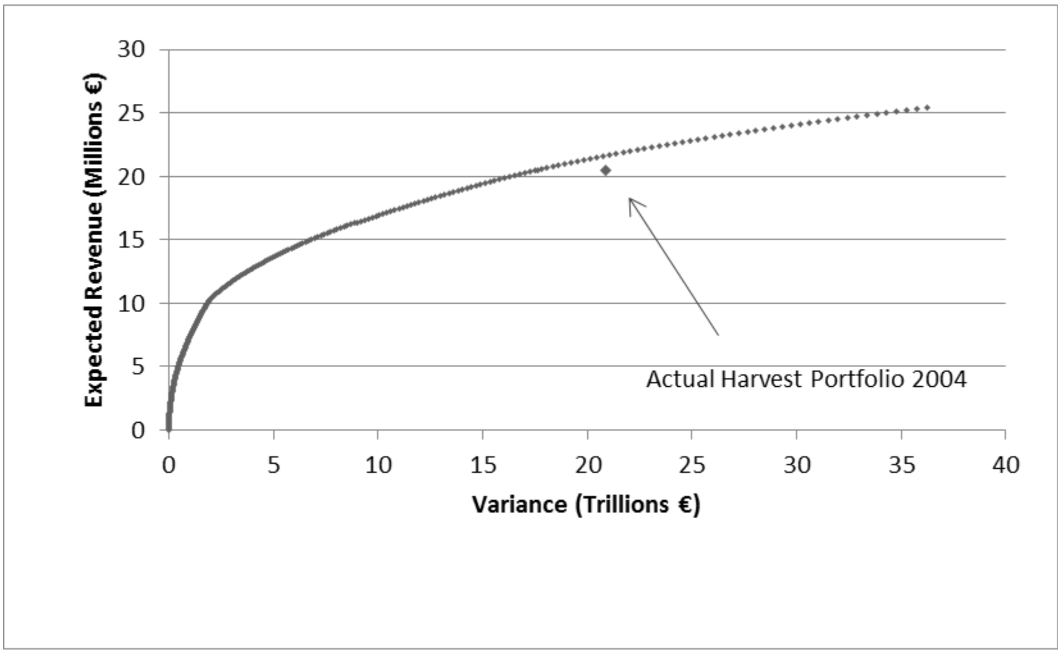

Fig. 2. Efficient Frontier of Harvest Options for the Hake, Monkfish and Megrim Fishery

The efficient frontier for the Hake, Monkfish and Megrim fishery is shown in Fig. 2. The frontier displays the set of possible minimum variance portfolios for a fleet target revenue of between zero and €25.43m (the maximum possible on the basis of historical averages). The point of interest in this scenario is the optimal portfolio for the fleet target revenue of €20.53m. To reiterate, €20.53m is the revenue that the fleet actually generated, and the concern is determining whether it was possible to do so with less exposure to variance. While the optimal portfolio at this level of target revenue lies on a point along the frontier, the actual harvest portfolio of 2004 is located below this line. This may highlight the potential for increased efficiency with respect to species selection, specifically, an 8.2% decrease in portfolio variance for the same expected revenue, but since there is no information on cost or technical interactions that determine the profitability/feasibility of achieving particular combinations of aggregate catch, it is not possible to determine this. It may be that procuring such a portfolio would be less risk-return efficient if profitability was the variable under consideration instead of revenue. The ex post mix of species in the actual 2004 harvest portfolio vs. the optimal weights are shown in Fig. 3.

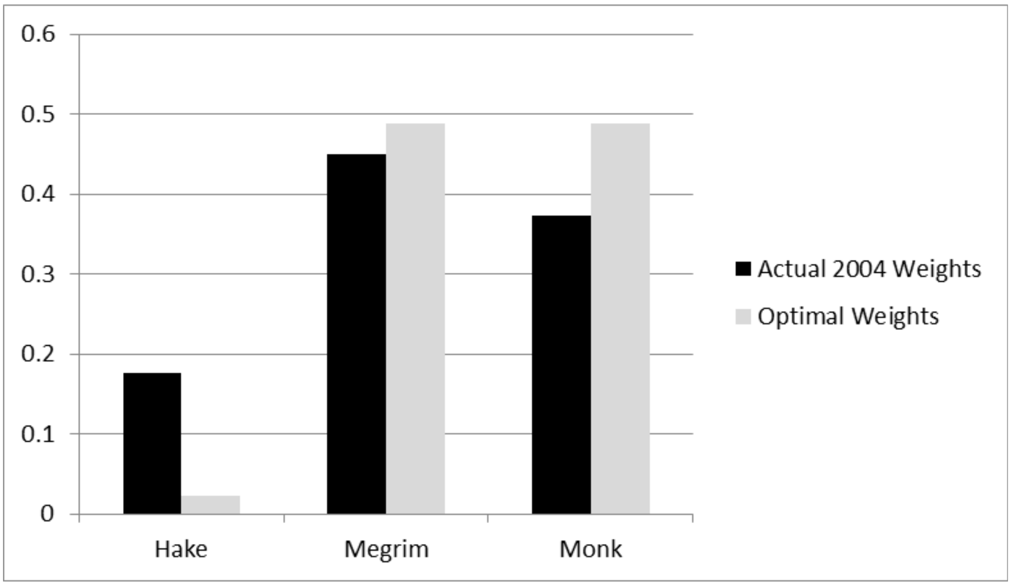

Fig. 3. Species Weights for Hake, Monkfish, Megrim Harvest Portfolio with Target Revenue of €20.53m

The Cod, Haddock and Whiting fishery generated € 13.16m in real dockside revenues in 2004. To attain this € 13.16m in revenue, it is estimated that the fleet selected a harvest portfolio with a standard deviation of €4.088m. The species weights selected through the portfolio optimization for a harvest portfolio of equal total revenue (€4.088m) resulted in a standard deviation of €3.92m, which suggests that at this level of target revenue there is scope for a 4.11% decrease in fleet portfolio variance. Actual harvest portfolio relative to the efficient frontier is shown in Fig. 4. Again, including variable costs in the analysis could very well undo the appearance of any possible efficiency gains. The ex post mix of species in the harvest portfolio vs. the optimal portfolio are shown in Fig. 5.

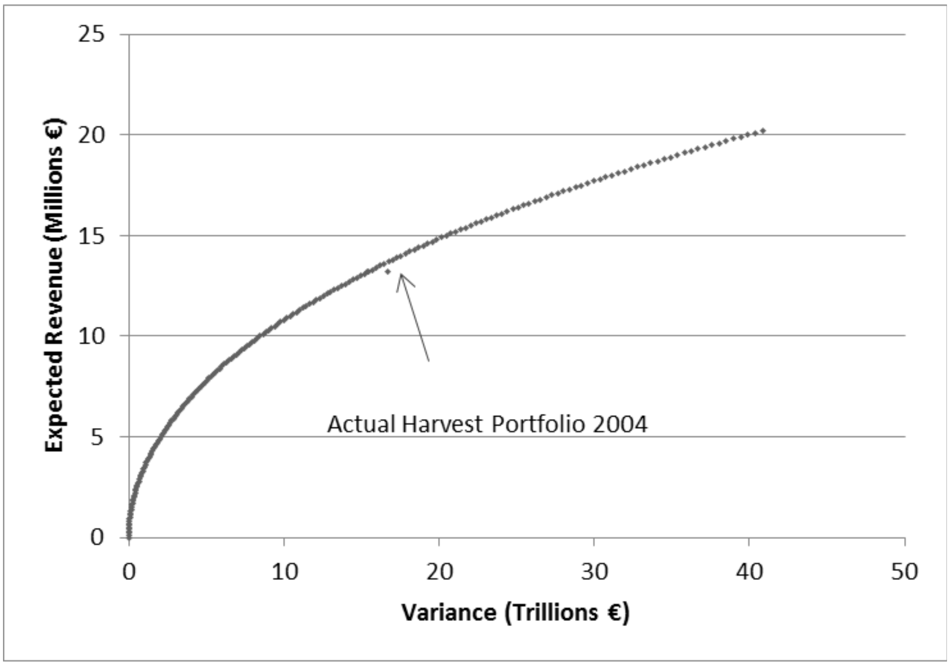

Fig. 4. Efficient Frontier of Harvest Options for the Cod Haddock Whiting Fishery. The actual harvest portfolio of 2004 is the point lying below the efficient frontier

These results suggest that if scope for risk-revenue trade-off efficiency gains exist, they are not large, and may even be less if variable costs are considered. As such, it suggests that fisher's already balance targeting strategies between revenue and risk well. From Fig.6 it is clear that some species, such as Cod, are more important in the real world than in the optimization. The historical significance of Cod in Ireland, and the development of an entire fishing culture around it, can easily explain why it features so prominently in the actual fleet harvest portfolio, despite the fact that it has a lower efficient revenue to risk profile (see Table 2). It is outside the scope of this paper to factor qualitative observations such as this into the framework, but it is feasible that any characteristics of a particular species that affects the fishing-community utility function in a non-monetary way could be incorporated into such an analysis as this.

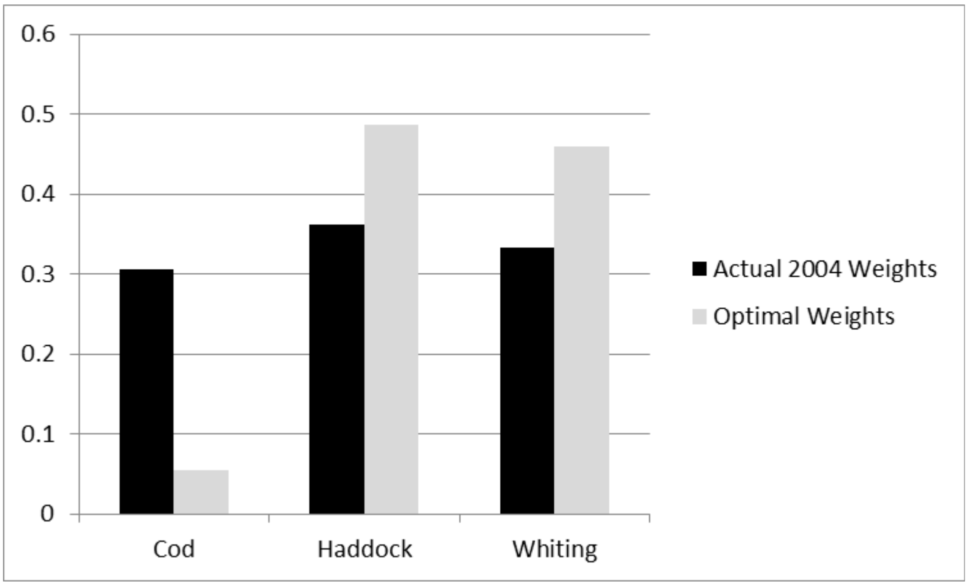

Fig. 5. Species Weights for Cod, Haddock, Whiting Harvest Portfolio with Target Revenue of €13.16m

Scenario 2: Precautionary Measure in the Cod, Haddock, Whiting Fishery

Cod, Haddock and Whiting stocks around Ireland have all declined in recent years; 78%, 39% and 57% respectively between 1995 and 2004. According to Cawley et al.(2006), Cod is severely depleted in all Irish waters, Whiting in the Irish Sea and off the north-west coast, and Haddock, while not overly depleted, is considered over-exploited. In this second scenario, the hypothetical precautionary measure for a single species is a 50% reduction in the contribution that the Haddock stock can make to the total harvest portfolio. This precautionary quota constraint was applied to Haddock because Cod is already severely depleted and there is little scope left for further quota restrictions. Once this constraint has been included in the optimisation, fisher's must choose a different set of species to achieve the same amount of revenue, maximizing their utility by selecting the portfolio with the lowest associated risk. The species weights of the resulting harvest portfolio are shown in Fig. 6.

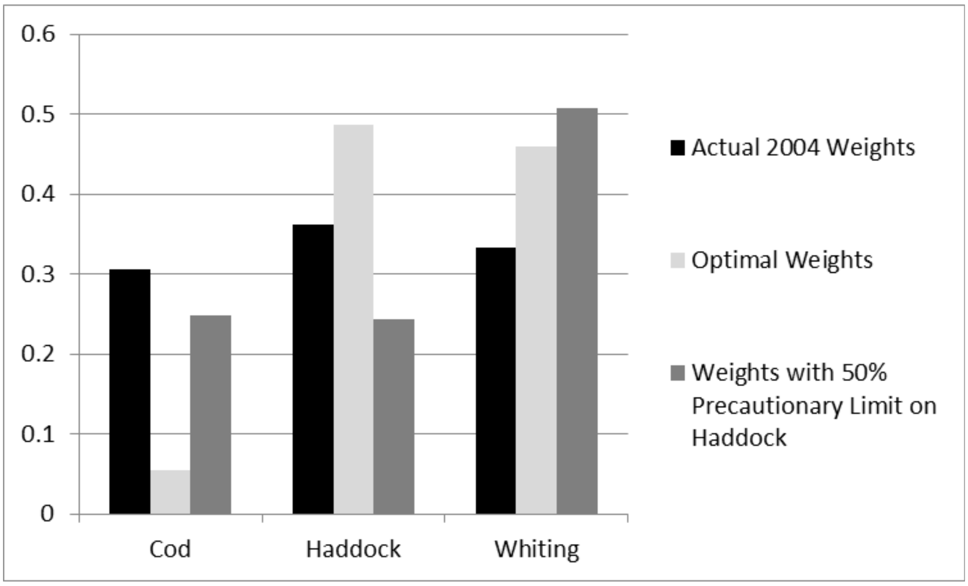

Fig. 6. Species Weights for the Cod, Haddock and Whiting Harvest Portfolio with Target Revenue of €13.16m under Actual Status Quo, Optimal Status Quo and Precautionary Scenarios

Given that it is an imposed constraint, the share of the fleet portfolio dedicated to Haddock is halved and is now 24.3%. While the expected revenue of the harvest portfolio has remained the same, the risk associated with it has increased, albeit by the least amount possible, therefore utility has fallen. Cod, which had previously accounted for 5.5% of the optimal portfolio without the constraint on Haddock, now accounts for 25%. Whiting has increased from 46% to 50.8%. The results show that Cod would be the main species to which effort from Haddock would be redirected if the fisher were free to do so (unconstrained by Cod fishing restrictions). This is not simply because Cod is a more attractive option (results from scenario 1 show that it is less efficient). A closer examination of Whiting reveals the fact that a 50.8% share of a portfolio with total expected revenue of € 13.16m is €6.69m (the expected revenue for Whiting is calculated using a decay factor of .741). In other words, this is the maximum expected revenue of Whiting based on historical averages.

If the system (biological or regulatory) allowed for any higher revenues to be generated from Whiting, then it would form an even greater fraction of the harvest portfolio when the precautionary constraint was placed upon Haddock. The fraction of

Cod increased because it was not optimal to have a higher percentage of it at the outset, so it had not reached its limit. It therefore had more capacity within the optimization as an "alternative opportunity". The percentage of Cod, Haddock and Whiting in the actual 2004 harvest portfolio was 30.6%, 36.2% and 33.3% respectively. So in reality, this capacity in the stocks of Cod does not exist. The result shows that a constraint on the permitted catch of Haddock in the fishery causes increased effort to be directed toward other species in the fishery. However, catches of Cod and Whiting are already at their upper bounds, or beyond them. Thus the multi-species impact of a precautionary constraint on any one of these species is therefore very unlikely to remain within the fishery.

Continuing with scenario 2, the impact that the precautionary measure has on the Hake, Monkfish Megrim fishery is considered. The actual 2004 Harvest portfolio for the two fisheries generated €33.68m in revenue. To attain this, the fleet selected a harvest portfolio with a standard deviation of €8.35m. The optimal harvest portfolio with revenue €33.68m would have had a standard deviation of €7.83m. Species weights for both portfolios can be seen in Fig. 7.

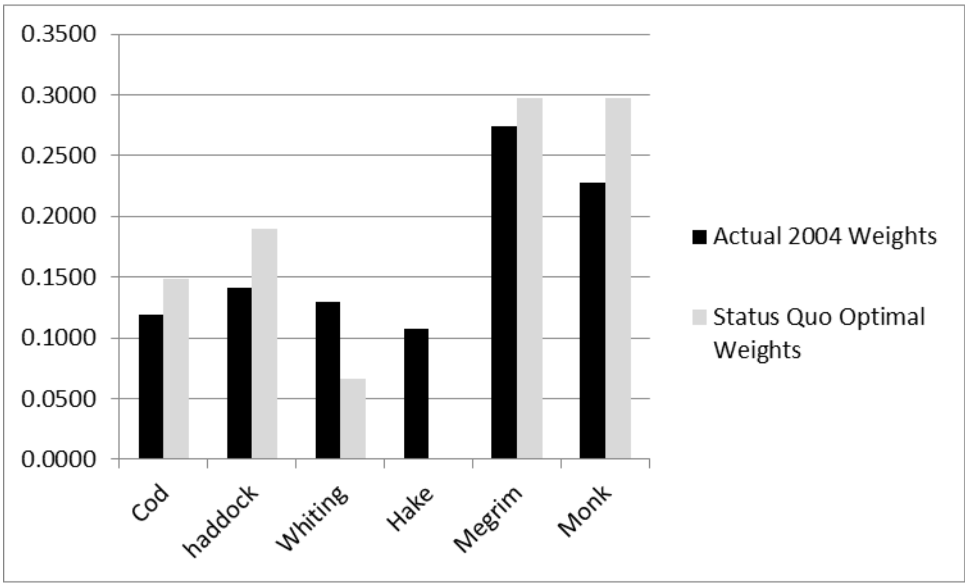

Fig. 7. Species Weights for both Fisheries and a Harvest Portfolio with Target Revenue €33.685m

Hake is not selected at all in the optimization as it is characterized by relatively low expected revenue (high market value but low historical quantities) and a relatively high variance and therefore only enters the optimal portfolio at target revenues above

€33.68m where the fleet will take on more risk for each unit of revenue. It also has a high positive covariance with Monkfish, which is far more efficient in terms of its revenue risk trade-off (see Tables 2 and 3). Upon inclusion of the precautionary constraint on Haddock, the standard deviation of the optimal harvest portfolio with a total revenue of €33.68m rises to €8.013m (up from €7.83m). The species weights are shown in Fig. 8. The weighting of Megrim and Monkfish in the portfolio does not increase simply because it cannot; upper bounds on weighting of these species in the portfolio had already been reached before the additional constraint; approximately 30% each of the €33.68m total revenue. However, in the actual 2004 harvest portfolio, Megrim and Monkfish constituted just 27.4% and 22.7% respectively. Given the attractive risk revenue profiles of these stocks, it is therefore *very* likely that a precautionary measure on Haddock would have a knock on affect in the Hake, Monkfish and Megrim fishery.

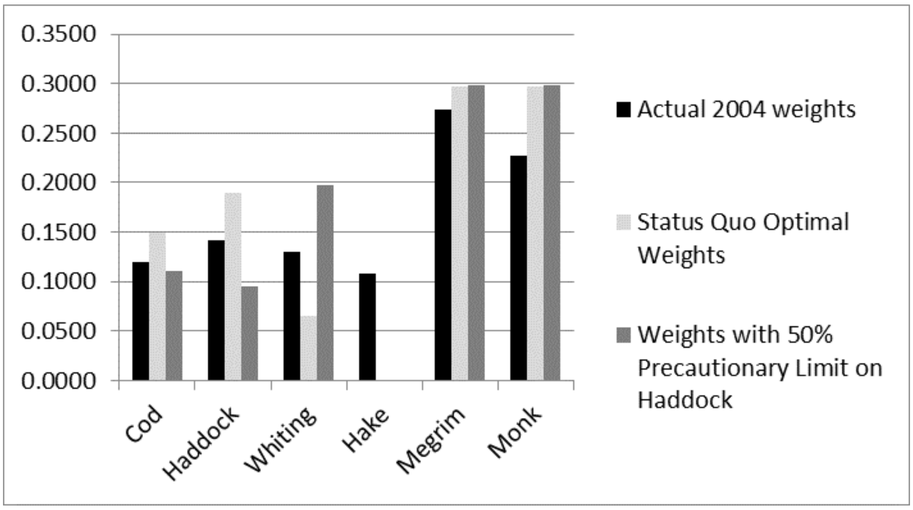

Fig. 8. Species Weights for both Fisheries and a Harvest Portfolio with Target Revenue

Scenario 3: Precautionary Measures in the Hake Monkfish Megrim Fishery

ICES claim that Monkfish is not over-exploited in relation to its precautionary limit. However, because of the severe decline of whitefish stocks such as Cod and Whiting in recent years, many of the traditional fleets have been affected. The result is an influx of new vessels into alternative fisheries. Where stocks in an alternative fishery are already exploited beyond optimal levels, its capacity to absorb increased exploitation rates is limited.

In this scenario, a hypothetical precautionary quota restriction on Monkfish is implemented. Fig. 9 shows the impact of a 50% reduction in the contribution Monkfish can make to the harvest portfolio. The new optimal fleet harvest portfolio has a standard deviation of €8.471m.

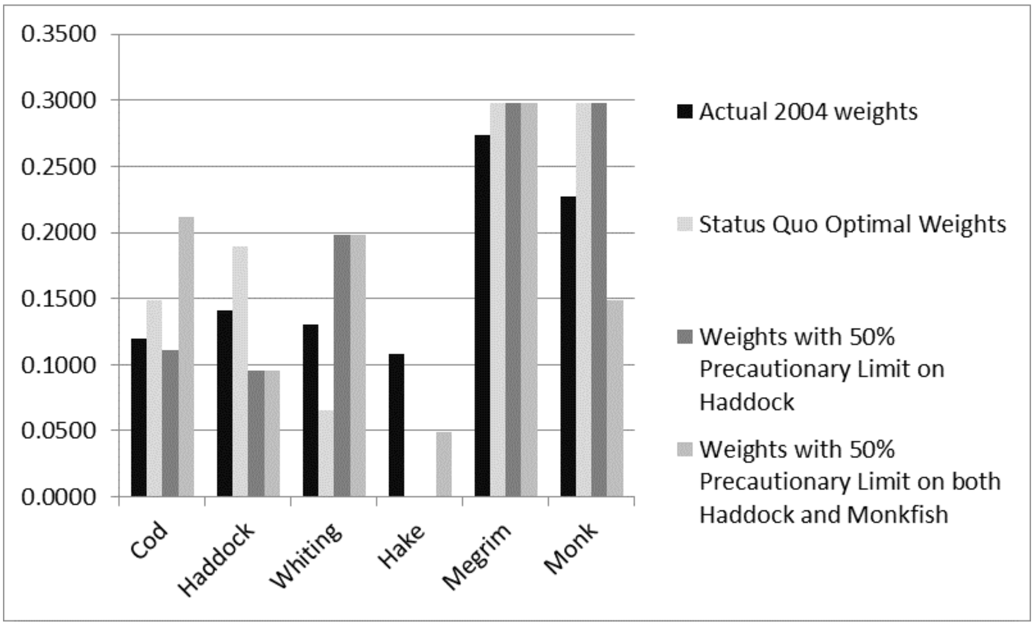

Fig. 9. Species Weights for both Fisheries and a Harvest Portfolio with Target Revenue €33.685m under Actual Status Quo, Optimal Status Quo and Precautionary Scenarios for Multiple Species

When precautionary constraints are placed on both Haddock and Monkfish, fisher utility is further reduced by forcing fishers to select a harvest portfolio with a higher level of risk in order to maintain status quo revenues. As the results suggest and as is outlined in the Cawley report, declining whitefish stocks force fishing effort into the Hake, Megrim and Monkfish fishery. However given a scenario of overfishing and precautionary quota constraints on Monkfish, expected revenues from this fishery diminish and the weighting of Cod in the harvest portfolio increases again. This suggests that any upside for Cod stocks that may arise from effort being redirected into the alternative fishery is beneficial only in the short term.

Discussion of the results hitherto have focused on precautionary measures of 50%. Such measures, while extreme, were chosen so as to highlight the dynamics of species-targeting behavioural responses. In reality, precautionary quota measures could be more adaptive, i.e., gradually increased over time. It is also interesting to note how the behavioural dynamics change when measures are more extreme than alluded to here. For this reason, Table 4 shows the resulting species portfolio weights when the precautionary measures graduate from 20%, to 50%, to 80%. Increasing the precautionary limits on Haddock and Monkfish to 80% highlights outcomes more pronouncedly, with the species weighting on Cod reaching its highest amongst all optimizations. Interestingly, it is infeasible to delineate a harvest portfolio with target revenue of €33.6m with precautionary limits this extreme. Despite a lower variance than harvest portfolios in other precautionary scenarios, the lower revenue associated with this portfolio results in the lowest possible utility for fishers amongst all scenarios. This captures the reality that fisheries today face. In the medium term, the impact of declining stocks can be offset by bearing more risk or investing in superior fishing technology. Eventually however, stocks are driven so low, that the only possible outcome is a fall in revenue. This is a classic result of overcapacity, and the impetus for measures such as property rights and fleet decommissioning.

Table 4. Species Weights under Various Precautionary Scenarios

Harvest Portfolio		Cod	Haddock	Whiting	Hake	Megrim	Monkfish	Portfolio Revenue (Euros)	St. Dev
2004 Observed		.1195	.1413	.1299	.1079	.2741	.2273	33,684,782.61	8,348,096
Precautionary Reduction in Haddock	Precautionary Reduction in Monkfish								
0%	0%	.1489	.1898	.0659	0	.2977	.2977	33,684,782.61	7,833,068
20%	0%	.13	.152	.123	0	.298	.298	33,684,782.61	7,898,937

	20%	.212	.038	.198	.016	.298	.238	33,684,782.61	7,986,150
	50%	.212	.038	.198	.105	.298	.149	33,684,782.61	8,188,782
	80%	.219	.039	.206	.165	.308	.062	33,684,782.61	8,487,715
50%	0%	.111	.095	.198	0	.298	.298	33,684,782.61	8,013,212
	20%	.171	.095	.198	0	.298	.238	33,684,782.61	8,130,674
	50%	.212	.095	.198	.049	.298	.149	33,684,782.61	8,397,052
	80%	.212	.095	.198	.138	.298	.06	33,684,782.61	8,777,342
80%	0%	.168	.038	.198	0	.298	.298	33,684,782.61	8,166,559
	20%	.212	.038	.198	.016	.298	.238	33,684,782.61	8,3284,38
	50%	.212	.038	.198	.105	.298	.149	33,684,782.61	8,677,458.
	80%	.219	.039	.206	.165	.308	.062	32497390	8,642,289

6. Discussion and Conclusions.

This paper used the portfolio theory framework to develop a model which might assist fishery managers and policy makers to better predict the likely changes in the composition of fisher's harvest portfolio when precautionary measures on a single species are implemented. Fleet expectations about species revenues and covariances were modelled for the Irish Cod, Haddock and Whiting and Hake, Monkfish, and Megrim fisheries using the historical averages of species prices and landed quantities. An exponential weighting factor, which captured fisher's inclination to weight recent events more highly in forming expectations about future events, was also used. Actual vs. optimal status quo species selection and the scope for potential efficiency gains were shown, both in terms of species weights and relativity to the efficient frontier. Hypothetical precautionary scenarios/constraints were also set out, and the potential impact of these measures on fisher's targeting choices and species weights in the harvest portfolio selection were assessed.

The results of the comparison between the actual and optimal status quo scenarios suggest that the Cod, Haddock and Whiting and Hake, Monk Megrim fisheries may already engage in return risk balancing behaviour, since the difference between portfolios was small and given data on cost and technical interactions, may be even less substantial.

This paper demonstrates how the portfolio methodology could be employed to accurately predict how a fleet might actually respond to various catch constraints. To be of real practical use however, further development would be necessary, particularly in terms of data availability. The major data limitations were the lack of data on costs and technical interactions; these factors play a large role in determining the profitability and feasibility of achieving particular combinations of aggregate catch in a multispecies fishery. For the methodology to be developed further into something that could actually assist in multispecies management decisions, such data would have to be included. The model employed in this paper minimised the consequences of omitting cost data by selecting fisheries with similar variable costs amongst species and little to no fixed cost fishery entry barriers. Where there is a lack of cost data for a fishery, the use of cost simulations such as those demonstrated by Rockmann et al. (2009) may be of use.

A further problem is with the estimates of variance. The variance measure is the variance in annual total revenue over time which could be related to many time variant factors as opposed to randomly and independently over time. A further point is that only the variance in revenues for the Irish fleet are considered, which only catch a fraction of the total catch of the species under study. Thus one cannot choose a set of harvest targets and assume the distribution of expected returns around those targets is well represented by the variance of revenues over the prior years. Despite these weaknesses, there is scope for the portfolio approach to be improved upon by inclusion of catch data for the entire fishery (not just Irish fleet) and perhaps the inclusion of more frequently observed species catch quantities and prices.

Despite these shortcomings in this application of portfolio theory, there is scope for the framework to assist fishery managers in a multispecies fishery management. In particular, the framework may lend itself well to the task of setting multiple TACs across species. The ability to predict the direction into which fishing fleet will refocus targeting effort once quotas have shifted can help to inform policy makers about quotas required for other relevant species.

The model highlighted the already identified problem of traditional whitefish fleets entering alternative fisheries, such as the Hake, Monkfish and Megrim fishery. Its focus on predicted behavioural responses to protective measures allows for the factoring of these changes into management decisions so as to avoid unpredicted changes in fishery targeting behaviour. Under the third scenario, wherein precautionary measures were placed on Monkfish, the short term alleviation of fishing effort on the traditional whitefish stocks was reversed, and effort again refocused on stocks like Cod and Whiting in the optimizations. This demonstrated the capacity of the model to play a role in more forward thinking planning when adopting a precautionary approach. Ultimately, there is little benefit to alleviating the strain on one stock by temporarily allowing effort to focus on another if in the long term, decline in the stocks of the "alternative" species led fishers back to their original species targeting behaviour (with higher levels of revenue variability and potentially lower income). Overall then, while development of the methodology and improvement in data would be needed for practical use, the results suggest that there is scope for the portfolio theory framework to add value and assist fisheries managers in the multi-species-based fisheries management.

One of the results of the analysis was that precautionary constraints in the Cod, Haddock and Whiting fishery could indirectly contribute to an over-capacity in the Hake, Monkfish and Megrim fishery due to displacement of traditional fishing effort. One of the ways in which fishery managers try to overcome the problem of over-capacity is to balance the fleets harvest levels with stock capacity. Where negative multi-species/multi-fishery impacts of a protective measure are predicted, a similar structural rationalisation may be appropriate in the fisheries affected instead of relying on more precautionary quotas alone. The recent decommissioning of Irish whitefish fleet is a good example of this (Cawley et al. 2006). The fishery portfolio method may be of particular use when considering any measures (such as decommissioning) that can precede the undesirable displacement of fishing effort following a precautionary measure.

Rights-based measures may be warranted to ensure fleet capacity and harvest rates are maintained at sustainable levels. Indeed, the need for a portfolio approach to fisheries management to be combined with clearly defined harvesting/property rights and institutions has already been stressed by some (Hanna 1998; Edwards et al. 2004; 2005). In the analysis, it is much more likely that fishers would seek efficient risk-return outcomes if they acted as a single group maximising the value of the output in the entire fishery.

Another issue limiting the usefulness of the portfolio approach is the lack of species specificity in fishing gears. Where a fishing strategy does not differentiate between two or more species, optimal fishing may not coincide with the species weights resulting from portfolio optimizations. Increased species specific fishing gears, which are becoming increasingly emphasised given EU policy developments on discard bans, will therefore improve the usefulness of the portfolio approach and contribute to more ecosystem-based and sustainable fishing practice. Further multi-disciplinary work, such as collaboration with fisheries scientists/managers in the design and application of the portfolio methodology may also led to improvements in the models usefulness. Finally, the comparison of species weights resulting from alternative scenarios with the output of structural ecosystem models is another avenue for future research that could yield informative insights for fisheries management

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[i] In an extreme case of supply reduction for any species, such as that following reduction of 50% of the haddock quota, it is possible that the assumption of exogeneity could be violated. In such a scenario, inclusion of price responses to supply changes would allow for a more complete analysis.

[ii] The portfolio analysis described above was carried out in the software package GAMS. The algorithm used in GAMS/CONOPT is based on the GRG algorithm first suggested by Abadie and Carpentier (1969). Details on the algorithm can be found in Drud (1985 and 1992). The procedure first uses initial values to compute a feasible solution. Then the constraints and initial parameter values for the predictor variables are combined in order to calculate a gradient for the goodness of fit measure that can allow updating of predictor variable parameters from their initial values. If the change in the parameters along the calculated gradient equals or is below the minimum threshold for goodness of fit change, the algorithm is said to have converged. Otherwise parameters that can be profitably updated are changed in the calculated search direction using a pseudo-Newton updating process. The procedure continues until either: the minimum threshold for goodness of fit change is achieved, conditional upon the specific parametric constraints; or, the maximum allowable number of algorithm iterations is achieved. If this threshold minimum is not achieved in the maximum allowable algorithm iterations, the algorithm is said to not have converged.

[2] Economic Exclusion Zones can be defined as the territorial waters of a nation, extending to 12 nautical miles from the baseline.

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[3] First established under the 1983 review of the CFP, this method of allocation was initially adopted to promote political stability, allowing each member state's fishing effort to remain constant, relative to that of others. It also gives preference to the fishing dependant countries of Northern Europe under the Hague Resolution (Boude, et. al., 2001).

[4] TACs are placed on each fishing zone, within EU waters. These limits are determined by ecological surveys and analyses, with final catch levels set annually by a meeting of the European Commission of Fisheries Ministers.

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