Measuring the value of ecosystem-based fisheries management using financial portfolio theory

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Abstract

Ecosystem-based fisheries management (EBFM) aims to maintain healthy ecosystems and the fisheries they support. However, although claimed by several international regulations, currently it is not applied within the EU.

In this work we highlight the benefits that result from adopting the EBFM. We do it by comparing EBFM implementation with the more traditional single stock approach. We show how portfolio theory can contribute to the use of EBFM, by means of selecting an optimal portfolio that maximizes average revenues and minimizes its variance. Following this approach, we construct two efficient frontiers: the ecosystem efficient frontier, which takes stocks' interactions into account (the variance-covariance matrix), and the stock efficient frontier, which only considers individual stocks' variances.

Additionally, we define two risk gaps. The first gap measures the reduction of the standard deviation (per unit of revenue) that the fleet could have reached if they had decided to catch the optimal portfolio on the stock frontier instead of the historic portfolio. The second gap calculates the reduction in the standard deviation (per unit of revenue), when management moves from the portfolio on the stock frontier to the ecosystem frontier.

This methodological approach is then adapted to the Basque inshore fleet. According to our results, and taking the single-stock traditional approach as the benchmark, the EBFM would show the same historic revenue while facing a 23% lower level of risk. Alternatively, it would allow the same level of risk with a 21% increase in revenues.

Key-words

Inshore fishery, fishery management, stock correlations, portfolio theory, diversification

1. Introduction

Traditional Fisheries Management has focused on a Single Stock Management (SSM) approach, which often ignores important ecosystem considerations such as changes in habitats and ecosystem structure, bycatch and species interactions. Recently, an Ecosystem--Based Fisheries Management (EBFM) approach has been advocated to move beyond SSM by incorporating ecosystem considerations for the sustainable utilization of marine resources. The objective of

EBFM is to maintain healthy ecosystems and the fisheries they support (Pikitch et al. 2004). However, there are many challenges in the implementation of EBFM (Curtin and Prellezo 2010; Link and Browman 2017), the most common obstacles arising from the lack of empirical knowledge, that may be due to the reduced stakeholder engagement, the difficulties in establishing the appropriate temporal and spatial scales for management, a poor definition of objectives and management criteria and failure in the establishment of reference levels on which management decisions can be made (Link and Browman 2017, and the references therein).

Within the European Union (EU), important environmental directives such as the Water Framework Directive (EC, 2000) and the Marine Strategy Framework Directive (EC 2008b), as well as the Common Fisheries Policy (EU, 2013), call for an EBFM approach. However, the implementation of EBFM is considered a complex process not only within the EU (Prellezo and Curtin 2015) but also outside it (Gaichas et al. 2017). Due to the lack of consensus among experts and critics on how to implement EBFM, the development of this holistic framework is taking place in many different forms with various combinations of principles. Not surprisingly, some pragmatic EBFM methods have been derived from portfolio theory[1]. In finance, a portfolio is a group of assets and the investor's objective is to find the combination which minimizes the variance for a given expected return (Markowitz ,1952). Instead of analysing each asset independently, portfolio theory uses the correlations between assets to calculate the highest expected return with the same variance, or the same expected return with the lowest variance. Therefore, in fisheries management interpreting fish stocks as financial assets and considering multiple stocks jointly is consistent with an ecosystem—based approach in so far all-sort of species interdependencies are implicitly considered by including species revenues covariances.

Sanchirico et al. (2008) constitutes the pioneering analysis adapting financial portfolio theory as a method for EBFM that accounts for species interdependencies. Using data from the Chesapeake Bay for the period 1962—2003, they compare EBFM and SSM regimes by building two types of efficiency frontiers by means of including or excluding the species revenues covariances (stocks' interdependencies). Extending this work, Jin et al. (2016) propose a measure of excessive risk taking (the gap between the actual risk level borne by society and the minimized risk level) and show that portfolio analysis could inform managers at different levels of decision: large marine ecosystems, regions or fishing ports.

In this paper we combine the approaches adopted by Sanchirico et al. (2008) and Jin et al. (2016) and apply them to the Basque inshore fleet operating in ICES areas 7 and 8 for the period 2001-2015. Thus, we first draw the stock efficient frontier (SEF) in the expected revenue/variance space. We compute the portfolio with the minimum variance for a given average revenue: any other portfolio with the same revenue has a higher variance. Hence, the SEF comprises the best gross revenue-risk pairs of a catch portfolio. Instead, the ecosystem efficient frontier (EEF) follows the same approach but considers, in addition, the observed relationships (covariances) among the species caught.

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[1] The idea that a fishery resource could be seen as a (natural) capital asset goes back more than six decades to the work of Gordon (1954) and Scott (1955).

Using this approach we highlight the benefits of applying EBFM compared with SSM. We distinguish the incremental value added by the EBFM (in relation to SSM) from the value lost when fishing companies deviate from their optimal strategies. The reasons for these sub-optimal decisions may be diverse (incomplete information and biased expectations, among others).

Therefore, the objective of this paper is twofold. First, it aims to measure the risk attached to the actual landing profile of the Basque inshore fleet and compare it with the outcome from applying the SEF. This calculation provides an assessment of the sub-optimal decisions made by the fishing operators. Second, it aims to measure the extra value of applying EBFM by means of comparing it with the SEF. The ultimate goal of this two-stage analysis is to identify the incremental value obtained (increased average revenue and decreased revenue variance) when optimizing catch composition to minimize revenue volatility. Additionally, this analysis is able to assess the difference in economic performance of the fleet derived from taking ecosystem considerations into account. In other words, our approach aims to measure the likely from adopting an EBFM approach. This goal entalis the use of two risk gap indicators that rely on the standard deviation (or volatility) of revenues per unit of revenue. The first indicator compares the historic portfolio with the current management; more specifically, it looks at the reduction of revenue volatility for a given revenue (or alternatively the gain in revenue for the same volatility) that fishermen could have reached if they had chosen a portfolio along the SEF. The second indicator measures the reduction of revenue volatility for a given revenue (or alternatively the gain in revenue for the same volatility) if fisheries managers had used species interaction thus selecting the portfolio along the EEF (instead of the SEF).

The conceptual framework is subsequently adapted to the Basque inshore fleet. There are two reasons for this. First, it responds to the availability of a long time series of daily fish sales data that allows us to exploit its richness to produce estimates of expected revenues and variances that can be used by local stakeholders to incorporate uncertainty into fisheries management decisions. Second, the fact that the anchovy fishery of the Bay of Biscay was closed from 2007 to 2009 offers us the opportunity to provide valuable insights into the interaction of component stocks and the targeted restoration of sensitive stocks. In this sense, the calculation of the two aforementioned risk gaps provides an alternative perspective to the assessment carried out by Andrés and Prellezo (2012) on the efficiency of the fishing firms' adaptation to the closure of this fishery.

The rest of the paper is organized as follows. Section 2 gives a general description of the data used and the portfolio theory applied to fisheries management. In Section 3, we look at the correlations between fish stocks, derive the efficient frontiers, compute the risk gaps and analyse the composition of the revenues. In Section 4 we draw the main conclusions and some policy implications.

2. Materials and methods

2.1 Study system

The Basque inshore fleet mainly operates in ICES areas 7 and 8 (Figure 1). In the first semester, the predominant landed fish stocks are the anchovy and mackerel and in the second semester the tunas (albacore and bluefin tuna). The fleet also catches other fish stocks such as sardine and horse mackerel (Iborra 2010; Andrés and Prellezo 2012; Prellezo and Iriondo 2016). The fleet is managed using a licence entry system and by Total Allowable Catch (TAC) and quotas at individual fish stock level.

Figure 1 around here

2.2 Data used

A dataset of daily sale notes from 2001 to 2015 of the Basque inshore fleet fishing vessels was used in this study (approximately 200,000 registers). They include the landings by day and vessel, in weight and value. In this dataset there is also extra information of fishing area and name of the vessel. Additionally, for those fish stocks managed using TACs (anchovy, horse mackerel, mackerel, bluefin tuna, blue whiting, ling, hake and anglerfish), TACs value were obtained from different official regulations (EU 2015 and previous years). The TAC is allocated to the different fleets through a quota share which was approximated by the average proportion of the landings of the fleet relative to the TAC.

Using these data, annual revenue was calculated. Species with a presence in only one of the years analysed were considered as anecdotal and grouped with the species with closer taxonomic classification when possible (and removed, when not). Finally, revenue data on the 35 observed fish stocks were translated into 2015 prices using the Spanish inflation rate (www.ine.es/calcula/).

Figure 2 shows the descriptive statistics of the fish stocks revenue until 2015. The total revenue and the composition vary year to year. It should be noted how from 2007 to 2009 the TAC of anchovy was set to zero for its biomass to recover (Andonegi et al. 2011).

Figure 2 around here

2.3 Modelling framework

2.3.1. Adapting portfolio theory

Our modelling framework combines the works of Sanchirico et al. (2008) and Jin et al. (2016). In our notation *t* stands for a specific year, μ_t is the vector of the species' weighted mean revenue between the first year (*t=1*) and year *t* and *w,* is the vector of revenue weights vector for *n* fish stocks (both μ_t and w have dimension *nx1*). The revenue of the portfolio in year *t* is $w'\mu_t$ and the variance $is\ \sigma_p^2$ $=w'\sum_t w$, where $\sum_t$ is the weighted variance-covariance matrix of the revenues obtained from the landings of each species:

$$\mu_{i,t} = \frac{\sum_{k=1}^{t} \lambda^{t-k+1}\, r_{i,k}}{\sum_{k=1}^{t} \lambda^{t-k+1}} \,,$$

$$\Sigma_{i,j,t} = \frac{\sum_{k=1}^{t} \lambda^{t-k+1} (r_{i,k} - \mu_{i,t})(r_{j,k} - \mu_{j,t})}{\sum_{k=1}^{t} \lambda^{t-k+1}} \,,$$

where $r_{i,k}$ denotes the revenue from species *i* in year *k*. To calculate the weighted mean revenue and the elements of the weighted variance-covariance matrix until year *t*, a decay factor λ is used (as in Jin et al. , 2016). It gives different options on how the "past" should be weighted.

When λ = 1, equal weighting is assumed for all the years (i.e. there is no decay). When λ=0.549, just 5% of the total weight remains after 5 years.

The variance of the portfolio is a function of the species variances and covariances (or correlation coefficients):

$$\sigma_p^2 = \ w' \sum w = \sum_{i=1}^{n} w_i^2 \sigma_i^2 + \sum_{i=1}^{n} \sum_{j \neq i} w_i w_j \sigma_i \sigma_j \rho_{ij}$$

where σ_i is the standard deviation of the i-th species, ρ_{ij} the correlation coefficient between species *i* and *j* and w_i the revenue weights of the species *i*. The weights and the standard deviation are always positive, so the only components that can reduce the portfolio variance are the correlations between species. Therefore, these correlations are a key element when discussing the outcome from applying the EBFM approach, and therefore, the base of our insights or interpretations.

To calculate the frontier in the year *t+1* for different revenue targets (M), the optimization problem to be solved is (Sanchirico et al. 2008):

$$\begin{aligned} &\min_{w}\ \mathrm{w}'\textstyle\sum_t \mathrm{w} \\ &s.t \begin{cases} w'\mu_t \geq M \\ 0 \leq w_{st} \leq w_{st}^{max}, \ \ \forall\ st \in \{1, \dots, n\} \end{cases} \end{aligned} \tag{1}$$

The first constraint ($w'\mu_t \geq M$) is necessary to ensure that the expected revenue is higher than the target revenue. The second constraint is named the *box constraint.* It is applied to all of the fish stocks and ensured that each weight is positive (the proportional revenue of the fish stock must be *0* or higher) and lower than the observed maximum value:

$$w_{st}^{max} = \frac{\gamma_{t,st} * B_{t,st}}{\Omega_{t,st}},$$

$$\Omega_{t,st} = \frac{\sum_{k=1}^{t} \lambda^{t-k+1}\ p_{st,k}\ y_{st,k}}{\sum_{k=1}^{t} \lambda^{t-k+1}\ p_{st,k}},$$

where $\gamma_{yr,st}$ is a sustainability parameter ($\gamma_{yr,st} = 1$), $B_{t,st}$ is the maximum sustainable catch and $\Omega_{t,st}$ is the weighted average of catch (Sanchirico et al. 2008), $p_{st,k}$ is the price and $y_{st,k}$ the catch of fish stock *st* in year *k*.

$B_{t,st}$ was calculated using maximum historic catch until t for the no regulated fish stocks and the sustainable limit for the fish stocks regulated by TACs:

$$B_{t,st} = \begin{cases} \max\limits_{1 \leq k \leq t} Catch_{k,st}, & \text{Stocks without TACs} \\ TAC_{t+1,st} \cdot QS_{st}, & \text{Stocks with TACs} \end{cases}$$

where QS_{st} is the quota share assigned to the fleets.

To compare SSM and EBFM, we compute two efficient frontiers in each year (SEF and EEF). The difference between them relies on the use or not of the variance-covariance matrix in the optimization problem (Eq. 1). To calculate the EEF, we use the information of the stock's interactions (full variance-covariance matrix), whereas in the SEF only the stocks' variances were used (i.e. the diagonal values of the variance-covariance matrix). The analysis was done using two different values of the decay factor, namely 1 and 0.549. We solve the quadratic programming problem using the quadprog package and the constrOptim function of stats package in R (R Core Team 2015).

2.3.2. Defining risk gaps

Jin et al. (2016) have proposed a measure of *excessive risk taking* defined as the difference between actual and optimal risk per unit of revenue. Extending this work, we proposed two different indicators that better fit with the objectives of our research. These indicators are based on the difference between the standard deviations (per unit of revenue) in two different settings:

1. The first indicator (gap 1) measures the reduction of the standard deviation per euro of revenue that the fleet could have had by choosing the optimal portfolio with the same expected return from the SEF. In other words, gap 1 is measuring the risk reduction to fishing firms in case of moving from the observed portfolio to the SEF optimal portfolio. In doing so we are measuring the potential efficiency gain from the fleet's point of view.
2. The second indicator (gap 2) measures the difference in standard deviation (per euro of revenue) that the fleet could have had if the fishery managers had used covariance data (EEF). Thus, this gap is measuring the value of introducing the EBFM approach in contrast of continuing with the current SSM approach (assuming that both are optimally used). By using gap 2 we are measuring the potential efficiency gained from the managers point of view.

Mathematically, these indicators are defined as follows:

$$gap\ 1\ (t) = \frac{\sigma_{p_1} - \sigma_{p_2}}{\sum_{i=1}^{n} r_{i,t}}$$

$$gap\ 2\ (t) = \frac{\sigma_{p_2} - \sigma_{p_3}}{\sum_{i=1}^{n} r_{i,t}}$$

where p_1 is the historic portfolio in year t and p_2 and p_3 are, the efficient portfolios on the SEF and EEF with the same mean revenue as the historic portfolio, respectively, and $r_{i,k}$ is the revenue of species *i* in year *t*.

2.3.3. Diversification and diversity

Revenue diversification is intuitively appealing. Nonetheless, in the mean-variance framework diversification does not always lead to lower levels of risk. In the simplest case with two single assets (say, C and S), one of them will be the least risky (say, S). Yet not all combinations of C and S will show a lower volatility than S. In other words, combining C and S will not always reduce risk below the one of S. It crucially depends on the correlation coefficient between C and S.

Further, as a general rule, we are analyzing optimal decisions along efficient frontiers in a two-dimensional space; they display an upward profile, so we face a trade-off. Maximizing the expected revenue for a given level of risk does not necessarily mean that this risk is small. Indeed, it can entail high doses of risk if it leads to concentrating efforts on the few most lucrative species.

A good way to assess supply risks (Kruyt et al. 2009) and/or technological lock-in (Sovacool 2011) is by means of diversity indices. Hill (1973) characterized a whole family of diversity measures:

$$\Delta_a = \left[\sum\nolimits_{i=1}^{I} p_i^a\right]^{\frac{1}{1-a}}, a \neq 1.$$

Here Δ_a stands for a particular index of diversity, p_i denotes (in economic terms) the relative share of alternative or option i in the portfolio under scrutiny (with i =1, 2,…, I), and the parameter a inversely measures the relative sensitivity of the resulting index to the presence of lower contributing options. Assuming $a = 1$ results in the so-called Shannon-Wiener diversity index:

$$SW = \sum\nolimits_{i=1}^{I} -p_i \ln(p_i).$$

A high value of the SW index corresponds to a diverse system. If SW<1 the system is highly concentrated and therefore prone to price hikes or interrupted supply. Instead, if $a = 2$, the reciprocal of the resulting expression is the Herfindahl-Hirschman concentration index:

$$HH = \sum\nolimits_{i=1}^{I} p_i^2.$$

The *HH* index is frequently used in the literature on industrial organization (Kruyt et al. 2009) to assess market concentration. It can range from 0 (competitive scenario) to 1 (pure monopoly). Antitrust authorities typically take a value *HH* < 0.1 or HH < 0.15 as indicating no concentration (EU 2004; U.S. Department of Justice and Federal Trade Commission 2010).

3. Results

3.1 Correlations among stocks

Figure 3 shows the revenue correlations of the fish stocks for the year 2015 under two different values of the decay factor (1 and 0.549). The stocks negatively correlated are shown in blue colour. Due to the negative correlations of some of the stock pairs, it makes sense to use the whole variance-covariance matrix to build the EEF to reduce the variance of the portfolio. It should be noted that this correlation matrix is different depending on the year and decay factor used.

Figure 3 around here

3.2 Comparison among historical portfolio and efficient frontiers

Figure 4 shows the revenue of the fleet in each year ($R_t = \sum_{i=1}^{n} r_{i,t}$) and standard deviation of that year's portfolio (represented with black dots). The blue lines represent the SEF portfolios. They are the solution to Eq. 1, hence they satisfy the sustainability constraints. They are optimal in the sense that there is no portfolio with the same expected revenue and lower volatility. The only way to obtain historic portfolios' standard deviations lower than standard deviation of the portfolio on the SEF is violating the upper bound of the *box constraint* (Eq. (1)) for some of the fish stocks ($w_{st,t} \geq w_{st,t}^{max}$). The relationship between the historic portfolio and the portfolio on SEF is captured by gap 1 and explained in the next section.

Next, we compute the EEF in each year using the whole variance-covariance matrix (red lines, in Figure 4). Comparing the SEF and EEF, by year and using TAC as the sustainability constraint, EEF provides lower variance for the same expected revenue (Figure 4, blue and red lines). This means that when the correlations between stocks revenues are considered, the variance of the portfolio is reduced.

Figure 4 around here

In 2010 and for $\lambda = 0.549$, there is no efficient portfolio (neither on SEF nor on EEF) with the same level of risk. It is impossible to find a portfolio which satisfies the sustainability constraints for that level of risk. In order to calculate the gains from using efficient portfolios, we decided to leave the year 2010 aside when computing the averages.

For the same revenue, we calculated the reduction of risk (sd) by choosing an efficient portfolio instead of the historic one (Table 1). Additionally, we also calculated the reduction of risk by using EEF instead of SEF (Table 1).

Table 1 around here

As shown in Table 1, SEF would allow the same historic revenue while bearing on average 23.97% and 12.53% less risk (for $\lambda = 1$ and $\lambda = 0.549$ respectively). Additionally, using the covariances, the portfolios on the EEF would have on average 23.63% and 27.73% less risk than those on the SEF.

We also calculate the potential increment of revenues allowed by choosing an efficient portfolio, while facing the same risk (standard deviation) as in the historical one (Table 2).

Table 2 around here

In Table 2 it is obtained how the fleet could potentially obtain 31.71% and 17.98% (for $\lambda = 1$ and $\lambda = 0.549$ respectively) more revenues for the same risk using the efficient portfolio in

SEF instead of historic portfolio. At the same time, it could also get 21.22% or19.14% more revenues using EEF portfolios instead of SEF portfolios.

Comparing the two decay factors, in the case of SEF the standard deviation of the optimal portfolios is higher with equal weighting (λ=1) than with decay (*λ=0.549).* However, in years 2010 and 2011 and for an expected return higher than $30\ million$ euros, the optimal portfolios on the EEF with λ= 0.549 had higher standard deviation than those with λ=1.

3.3 Risk gaps

Figure 5 shows the time path of the two gaps without decay (λ=1) and with decay (λ=0.549). In the case studied, the decay factor has not much influence on the overall trend and value of the two gaps except for the period 2009 to 2011. The main reason is that the anchovy fishery was closed during these years. In this regard, gap 1 increases from -0.02 to 0.414 in 2009-2010, which suggests that the adaptation strategy (the change on the portfolio composition under this new situation) was not the most appropriate. This sub-optimal adaptation could be caused by several reasons, including the market evolution or fish availability, and it is observed for the two decay factors considered.

Concerning the whole sample period 2006-2015, the fleet could have reduced the standard deviation for the same income in each year, by choosing the portfolio on the SEF (in Figure 5 it can be seen that gap 1 is positive every year, λ=1). Furthermore, the high variance to which the anchovy contributes, implies that the fleet took considerable risk capturing too much anchovy in 2010.

On the other hand, under λ=0.549, gap 1 is negative for the years 2007-2009. The only way to have a negative gap 1 in those years would be violating at least one of the restrictions. In this case, some of the historic weights are higher than the upper bound of the box constraint (Figure 6).

Figure 5 around here

Figure 6 around here

As for gap 2, the portfolio on the EEF has lower variance than the one on the SEF with the expected revenue fixed at the historic revenue in each year (Figure 5, gap 2). There is always a potential gain from using EBFM as compared to SSM, except for the year 2010 (for λ=0.549). This exception is explained below.

3.4 Landing portfolio diversity

First, we look at historical revenues from actual catches since the turn of the century. As shown in Table 3, the SW index is always higher than 1. The final value is 3.33% lower than the initial one, which points to a small overall drop in diversity. Conversely, the HH displays a 15.38% increase during this period.

Table 3 around here

Figure 7 displays the time path of both indexes. The whole period can be broken down into two parts. Until 2006 there is a sharp fall in the diversity of revenues from fishing activities. This is consistent with a steep rise in concentration. From then on, however, the opposite has happened. Managers seem to have sought a higher degree of diversity and this trend has gone hand in hand with a falling concentration.

Figure 7 around here

Henceforth, we concentrate on the last decade. In addition to the actual scenario we also consider the SEF and the EEF (in both cases assuming that λ equals either 1 or 0.549). Table 4 displays the results.

Table 4 around here

In all the cases the SW index is above the threshold 1.0; this suggests that the underlying fishing portfolio is relatively diversified (in terms of revenues). On the other hand, the HH index takes on values ranging between 0.19 and 0.44, which implies that these portfolios are somewhat concentrated. Regarding the parameter λ, its impact is not regular. For example, looking at the SW index and comparing the two SEF frontiers, in 2006 a lower value of λ (from 1.0 to 0.549) implies a fall in diversity (from 1.58 to 1.4), but in 2015 we observe a rise (from 1.74 to 1.91). If, instead, we take the HH index and compare the two EEF frontiers, in 2006 the same change in λ brings about a rise in concentration (from 0.3469 to 0.3685) but a fall in 2016 (from 0.31 to 0.2204).

Figure 8 shows the yearly changes in the SW index under the three main settings. As already mentioned, in this decade there appears to be a push toward greater diversity (blue line). Diversity is consistently higher in the SEF (orange line) than in the EEF (grey line). This suggests a possible mismatch between economic interests and environmental interests. Specifically, taking (revenue-based) covariances between species into account would imply less diversity. As suggested in Section 2, the starting point involves relatively stable revenues and we subsequently open the portfolio to other revenue sources with wild swings then diversification will not necessarily translate into lower revenue volatility (it depends on their correlation).

Figure 8 around here

Last, Figure 9 displays the yearly changes in the HH index in the three main settings. According to the actual revenues concentration has followed an overall declining path (blue line). The index corresponding to the EEF (grey line) evolves above the one of the SEF (orange line); again, 'naïve' intuition could suggest otherwise.

Figure 9 around here

4. Discussion and conclusions

Even though EBFM is considered in the EU's fisheries management basic regulation (CFP), it is not fully implemented within the EU. It is not easy to put EBFM into practice, and many difficulties remain (see Link and Browman (2017)). However, as we show in this paper, there is a benefit to be gained from implementing EBFM. Using the defined gaps, it is useful to compare the built portfolios in two steps. At one level, the fishing firms should try to reduce the difference between the standard deviation of historic portfolio and the one of the efficient portfolios on the SEF (gap 1). On the other hand, gap 2 informs fisheries managers on the reduction of the standard deviation due to the correlation between fish stocks, that is, the value of the EBFM in eliminating the (sub-optimal) decisions of the fishing firms.

Our work has several implications for different stakeholders involved in fisheries management. It helps in implementing, at least partially, the EBFM. Data used are being routinely collected under the Data Collection Framework (EC 2008). And the efficient frontier can be built while imosing constraints to ensure the sustainability of the fish stocks and, therefore, meet the management objectives.

In the EU, quotas among Member States are shared according to the relative stability principle (Hoefnagel et al. 2015). Nonetheless, conflicts arise when these Member States have to distribute their quota among their national fishing fleets. The EBFM could also help in reducing these conflicts. The optimal portfolio by fleet can be considered as a benchmark where the Member State sets all the stock shares among their different fleets. This optimal portfolio is giving management the optimal combination of fish stocks by fleet, and hence the excess and shortage of the optimal combination compared with their historical allocations. It should be noted that the demand coming from the fleets could be higher than the available fishing possibilities, creating the so-called bankruptcy problem (Gallastegui et al. 2003). This problem, although important, will have to be further analysed. However, by knowing the optimal portfolio of each fleet, their shares can be adjusted, and shortages can be shared among other fleets fishing the same stocks.

The diversification of stocks revenues has been increasing from 2006 to 2014 (lower HH). However, the efficient portfolios are less diversified than the historic ones. Therefore, higher diversity does not always provide more efficient portfolios (from the revenue viewpoint). Efficient portfolios can be less diverse than historic ones because of the high variance of fish stocks that are not target species (in this case, species without TAC). This implies that, when managing species with high variability, diversification of the portfolio is not, necessarily, the best strategy when measures to guarantee the sustainability of fish stocks (TAC, …) are in place.

Comparing the two decay factors used to calculate expected revenues and variance, we obtain equivalent results except for the year 2010. This exception is due to the high revenues of the anchovy after three years of a fishing ban. We consider that both decay factors can be used, although the $\lambda=0.549$ factor could be more appropriate when events like closing fisheries have occurred in previous recent years, since these extreme cases have high weight. The value obtained for gap 2 in 2010 shows one of the limitations of this approach. We considered landings as a proxy of relative abundance (the covariance matrix is calculated using revenues). This assumption can be used if the system is somehow stable; however, if (as in the case analysed) landings are set to zero (the closure of the anchovy fishery), this relationship is lost. This means that, if only a short period is considered (five years with $\lambda=0.549$), the covariance matrix is not giving the right ecosystem information, so it is better not to use it.

Overall, we conclude that the main loss of efficiency stems from the fishing firms' sub-optimal portfolio selection. In fact, according to our calculation and without decay, fishing firms could have obtained the same amount of gross revenue while bearing 23.97% less risk, for the whole period analysed. It is also true that the optimality calculated is subject to the availability of fish stocks, market interferences, and many other factors. This implies that gap 1 is to be taken as a maximum possible gain. Conversely, given that gap 2 is compared to this optimum, it should be interpreted as a minimum possible gain. This implies that EBFM would allow this fishery to obtain the same average revenue assuming 23.63% less risk.

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Figure Captions

Figure 1. Study area.

Figure 2: Total revenue in euros and the distribution of the revenue from 2001 to 2015. Different colours represent the species with highest revenue. All the remaining species are grouped in a single group named “Other” (in the work, the species are not grouped).

Figure 3: Correlations of the revenues of fish stocks in 2015 using equal weighting and decay factor 0.549.

Figure 4: Ecosystem (EEF) and stock (SEF) frontiers from 2006 to 2016 using both decay factors (0.549 and 1) and w^{max} calculated using TACs and maximum catch until year t (stocks without TACs). The points represent the revenue of the historic portfolios and standard deviation of the portfolio with historic weights.

Figure 5. Gap 1 and gap 2 from 2006 to 2015 using in the minimization problem equal weighting (blue lines) and decay factor (red lines).

Figure 6. Ratio between historic weight (w) and maximum weight for each fish stock and year ($\lambda=0.549$).

Figure 7. SW and HH index of historical revenues

Figure 8. The Shannon-Wiener index

Figure 9. The Herfindahl-Hirschman index

Figures

Figure 1

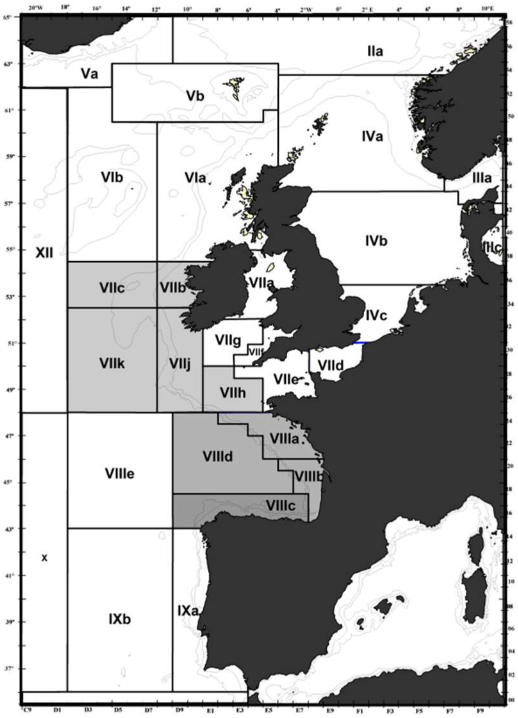


Figure 2

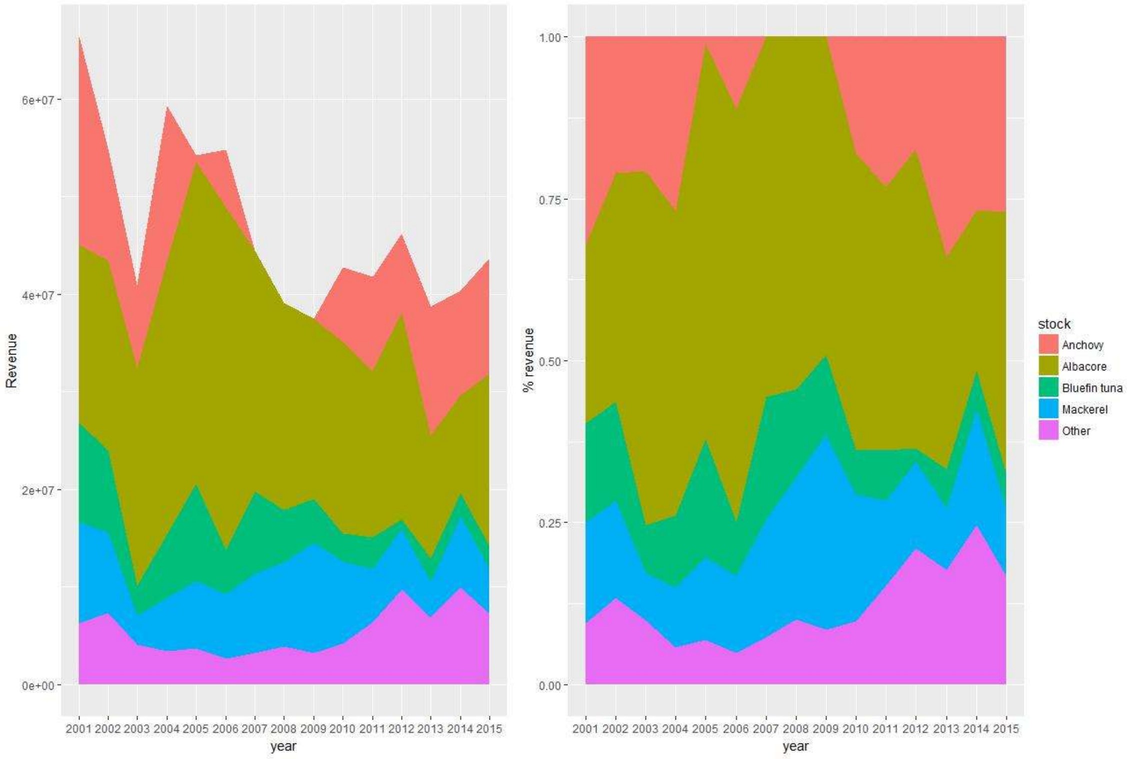
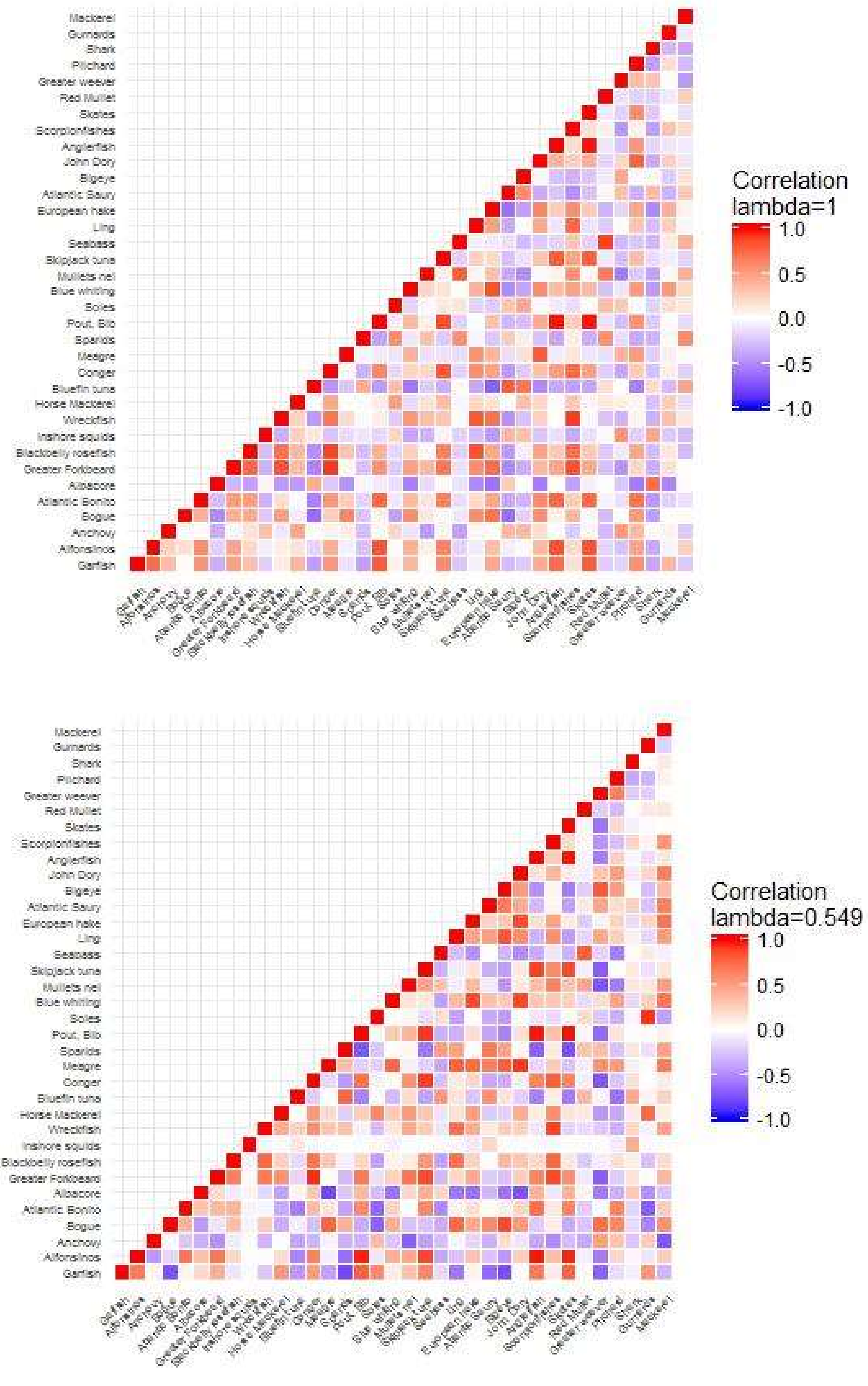
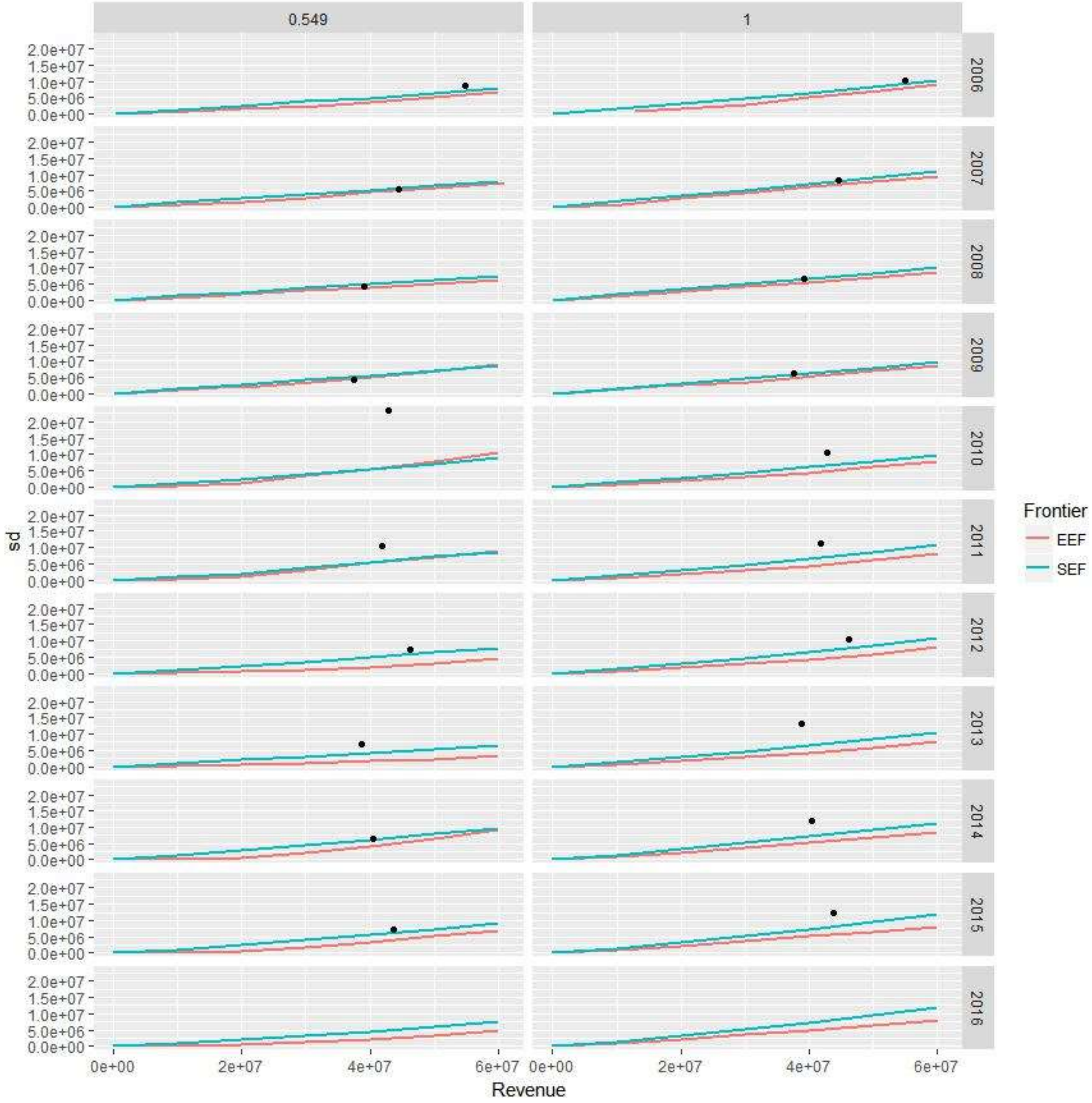

Revenue
6e+07
4e+07
2e+07
0e+00
year
2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015
% revenue
1.00
0.75
0.50
0.25
0.00
stock
Anchovy
Albacore
Bluefin tuna
Mackerel
Other

Figure 3


Mackerel
Gurnards
Shark
Pilchard
Greater weever
Red Mullet
Skates
Scorpionfishes
Anglerfish
John Dory
Bigeye
Atlantic Saury
European hake
Ling
Seabass
Skipjack tuna
Mullets nei
Blue whiting
Soles
Pout, Bib
Sparids
Meagre
Conger
Bluefin tuna
Horse Mackerel
Wreckfish
Inshore squids
Blackbelly rosefish
Greater Forkbeard
Albacore
Atlantic Bonito
Bogue
Anchovy
Alfonsinos
Garfish
Correlation
lambda=1
1.0
0.5
0.0
-0.5
-1.0
Correlation
lambda=0.549
1.0
0.5
0.0
-0.5
-1.0

520 **Figure 4**



521

522

523

Figure 5

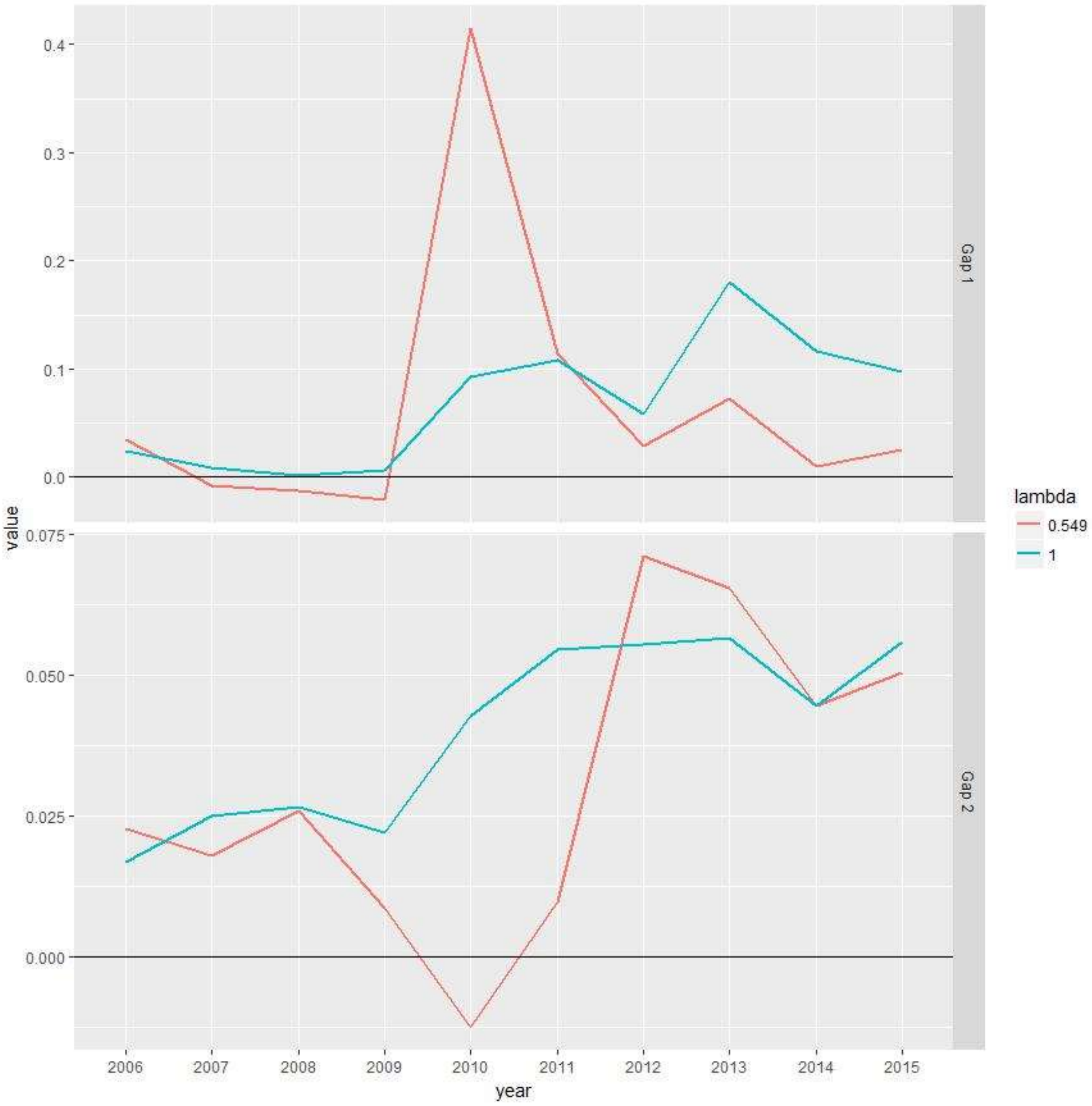
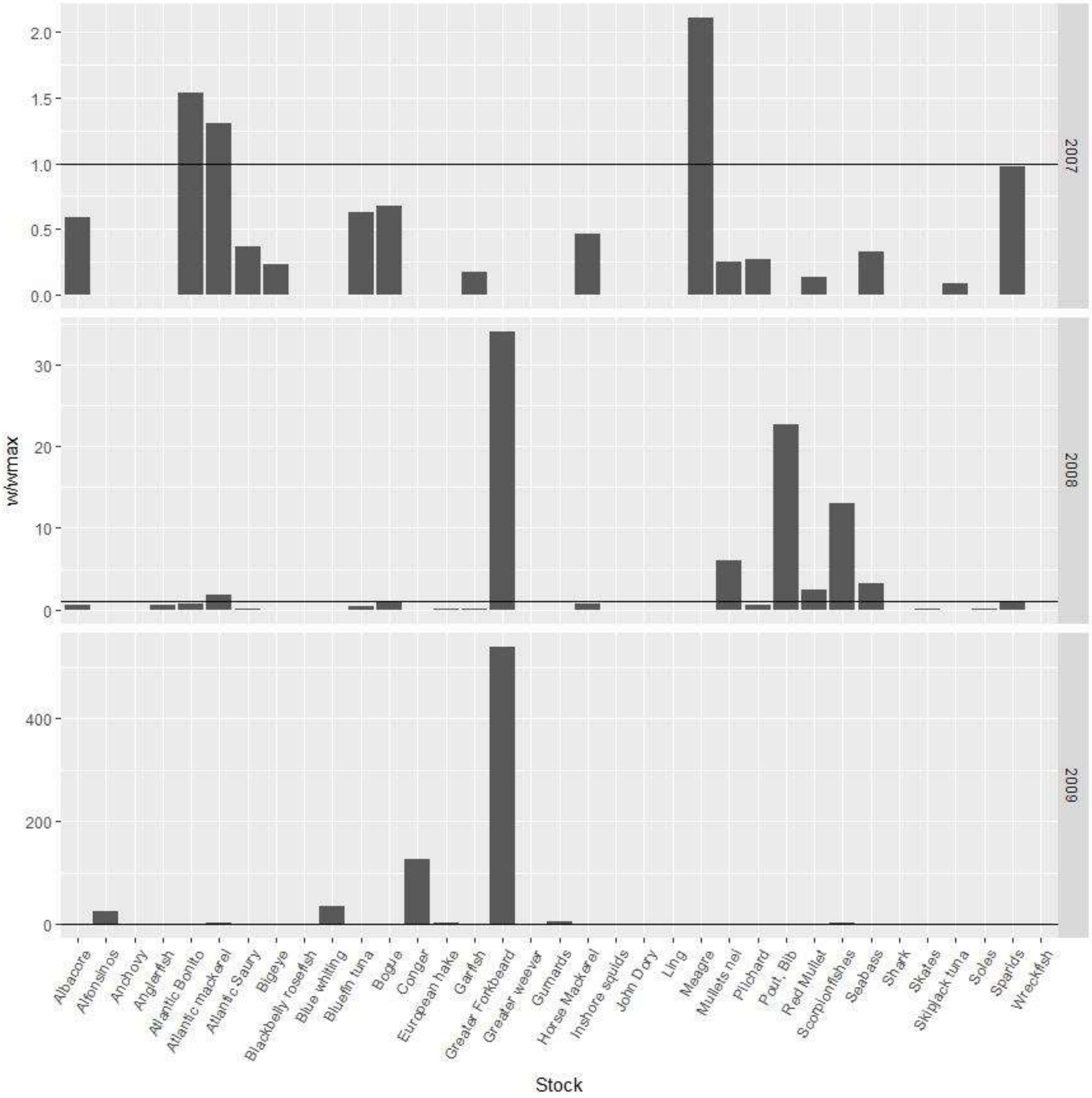
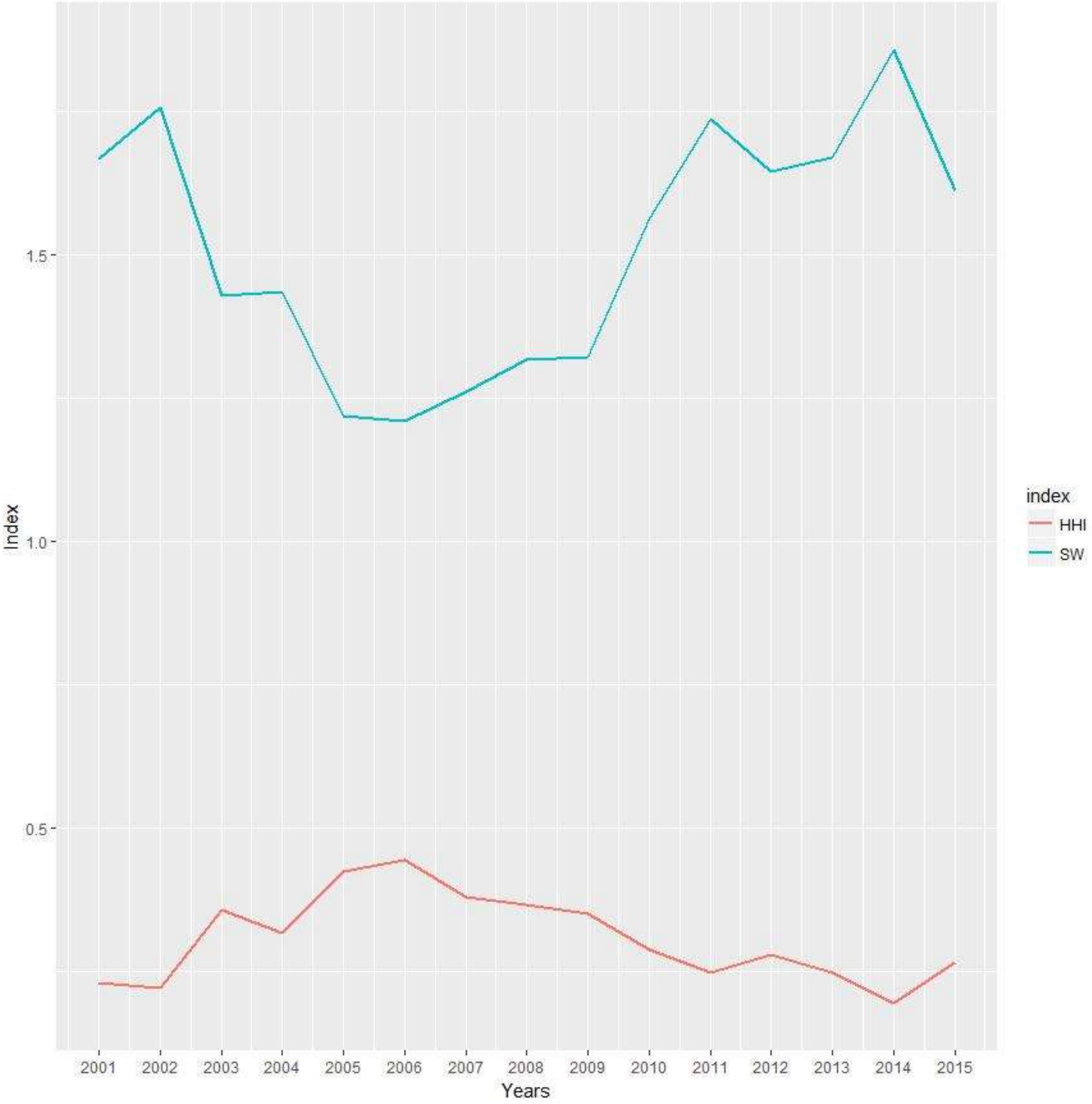

0.4
0.3
0.2
0.1
0.0
value
0.075
0.050
0.025
0.000
Gap 1
Gap 2
lambda
0.549
1
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
year

Figure 6


2007
2008
2009
w/wmax
0.0
0.5
1.0
1.5
2.0
0
10
20
30
0
200
400
Albacore
Alfonsinos
Anchovy
Anglerfish
Atlantic Bonito
Atlantic mackerel
Atlantic Saury
Bigeye
Blackbelly rosefish
Blue whiting
Bluefin tuna
Bogue
Conger
European hake
Garfish
Greater Forkbeard
Greater weever
Gurnards
Horse Mackerel
Inshore squids
John Dory
Ling
Meagre
Mullets nei
Pilchard
Pout, Bib
Red Mullet
Scorpionfishes
Seabass
Shark
Skates
Skipjack tuna
Soles
Sparids
Wreckfish
Stock

534 **Figure 7**



535

536

Figure 8

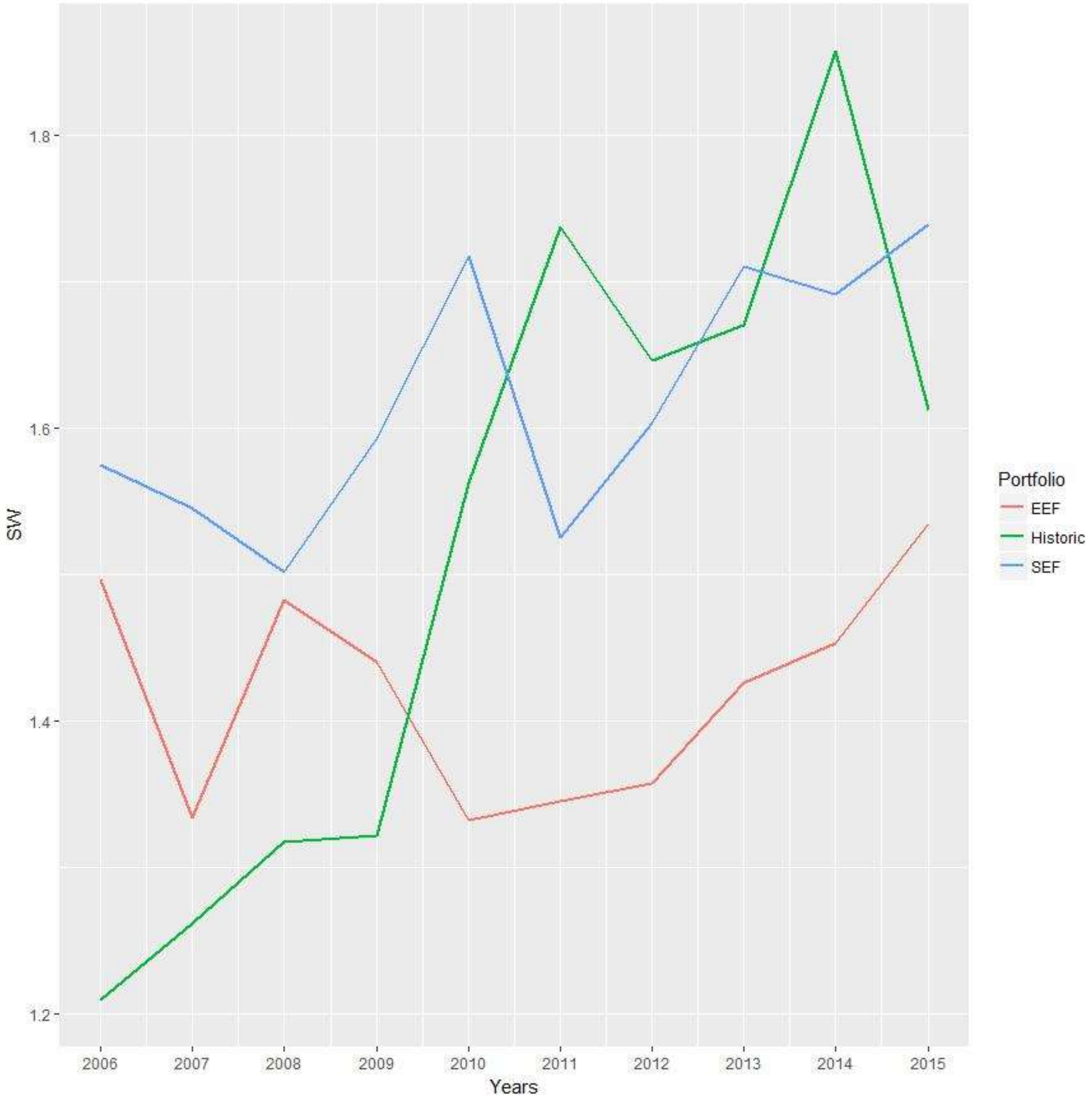
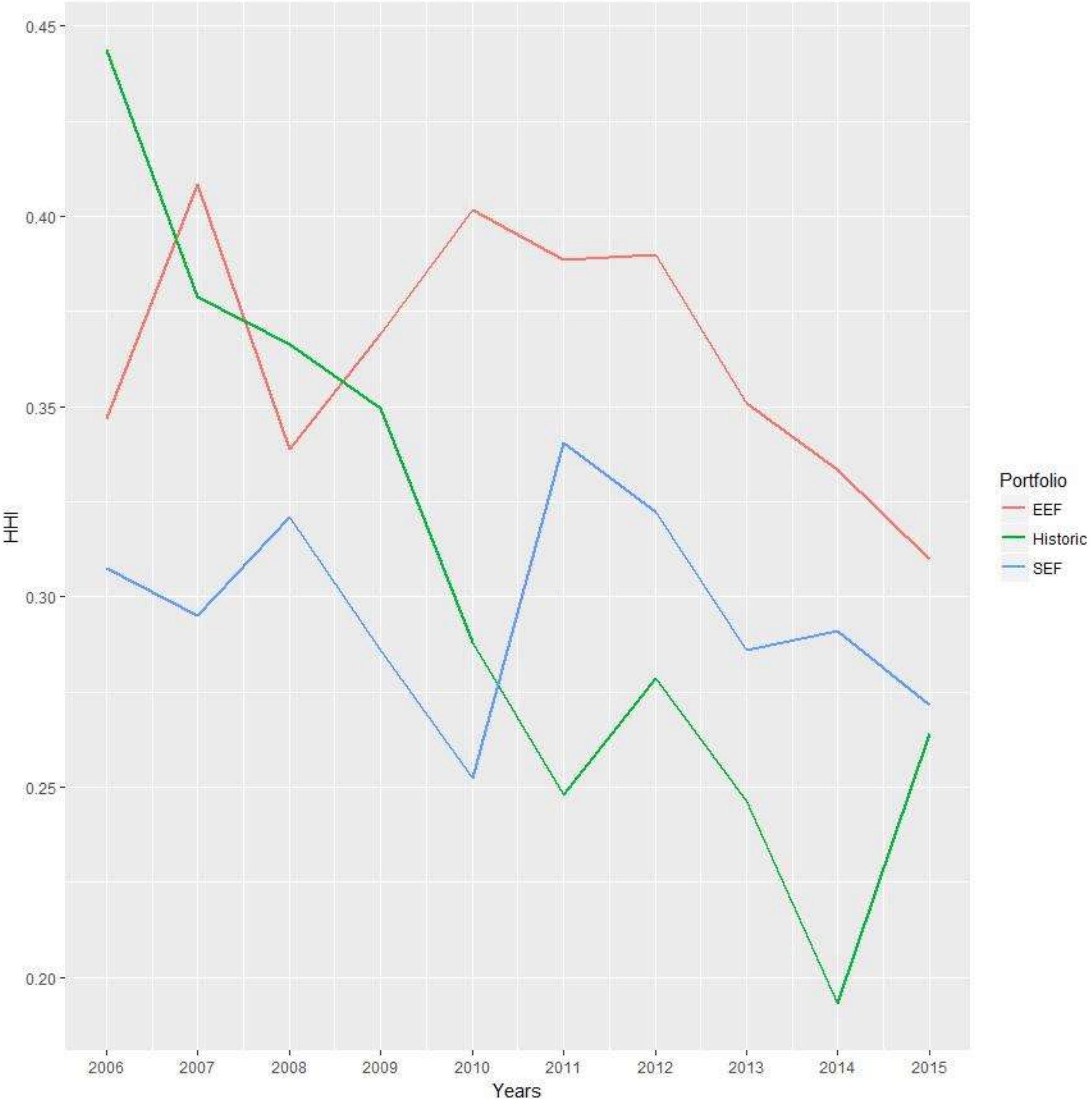

1.8
1.6
1.4
1.2
SW
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
Years
Portfolio
EEF
Historic
SEF

Figure 9


0.45
0.40
0.35
0.30
0.25
0.20
HHI
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
Years
Portfolio
EEF
Historic
SEF

Tables

Table 1: The mean of the reduction of standard deviation for the same revenues and using two decay factors

	Historic -> EEF (total)	Historic -> SEF	SEF -> EEF
λ = 1	40.48%	23.97%	23.63%
λ = 0.549	32.12%	12.53%	27.73%

Table 2: Increase of revenues (on average) for the same level of risk, using two decay factors

	Historic -> EEF (total)	Historic -> SEF	SEF -> EEF
λ = 1	$2.55 \cdot 10^{7}€\ (61.03\%)$	$1.33 \cdot 10^{7}€\ (31.71\%)$	$1.22 \cdot 10^{7}€\ (21.22\%)$
λ = 0.549	$1.74 \cdot 10^{7}€\ (40.45\%)$	$7.87 \cdot 10^{6}€\ (17.98\%)$	$9.55 \cdot 10^{6}€\ (19.14\%)$

Table 3. Diversity and concentration indexes based on historical revenues 2001-2015.

	2001	*2005*	*2010*	*2015*	*Average*
SW	1.6681	1.2186	1.5628	1.6125	1.5137
HH	0.2288	0.4229	0.2879	0.264	0.3065

Table 4. Diversity and concentration indexes across the five scenarios 2006-2015.

SW	*2006*	*2007*	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*
Historical	1.21	1.26	1.32	1.32	1.56	1.74	1.65	1.67	1.86	1.61
Stock F.	1.58	1.55	1.50	1.59	1.72	1.53	1.60	1.71	1.69	1.74
Stock (0.549)	1.40	1.29	1.43	1.51	1.54	1.36	1.57	1.41	1.78	1.91
Ecosystem F.	1.50	1.33	1.48	1.44	1.33	1.35	1.36	1.43	1.45	1.53
Ecosys(0.549)	1.45	1.32	1.39	1.59	1.47	1.32	1.66	1.79	1.84	1.78
HH										
Historical	0.444	0.379	0.366	0.35	0.288	0.248	0.279	0.246	0.193	0.264
Stock F.	0.308	0.295	0.321	0.286	0.252	0.340	0.322	0.286	0.291	0.271
Stock (0.549)	0.384	0.407	0.346	0.311	0.297	0.402	0.338	0.398	0.243	0.202
Ecosystem F.	0.347	0.408	0.339	0.369	0.402	0.389	0.39	0.351	0.334	0.31

Ecosys(0.549)	0.369	0.423	0.373	0.291	0.353	0.414	0.272	0.251	0.221	0.22