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An efficient portfolio approach towards ecosystem-based fisheries governance in EU

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A R T I C L E I N F O

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A B S T R A C T

In the framework of multispecies fisheries governance, the main objective of this paper is to apply modern portfolio theory (MPT) to the North-East Atlantic European fisheries, including all the key commercial fish species subject to total allowable catches (TAC) and quota regimes within the EU. This is done, first, quantifying the inherent return and risk of the potential fish portfolios and, secondly, estimating an individual constrained financial efficient frontier (FEF) for each of the nine fishing countries in the North-East Atlantic. Unlike previous studies in the field of financial fisheries economics, and due to its major robustness under non-normality and the presence of fat tails, we are using Conditional Value-at-Risk (CVaR) instead of the conventional mean-variance optimization (MVO) as the method to solve the optimization problem of minimizing risk under a set of alternative constraints so as to obtain the respective FEFs. Our results show that changing the species portfolio distribution, it would be possible to improve efficiency, that is to say, to simultaneously get increasing returns and decreasing risk levels. Moreover, this efficiency gain would be compatible with specific quota transfers among fishing countries.

1. Introduction

The lack of effective sustainable strategies to govern fisheries have encouraged scholars to propose an ecosystem-based fisheries management (EBFM) approach (Botsford et al., 1997; Pikitch et al., 2004; Beddington et al., 2007), switching from an individual species perspective to a multispecies one that explicitly puts the species' interactions in the centre of the debate (Werner and Gilliam, 1984; Cochrane, 1985; Marshall et al., 2018). Interaction among fish species takes for granted that the risks related to catching different species are correlated and, accordingly, considering all the species together in the overall ecosystem might be beneficial, not only to promote an efficient use of marine resources (Essington et al., 2006), but even to accomplish the triple bottom line of sustainability in fisheries (Halpern et al., 2013; Anderson et al., 2015; Asche et al., 2018; Liu et al., 2021; Marco et al., 2021).

The European Common Fisheries Policy (CFP) (EU, 2013) also calls for an EBFM approach to govern EU fisheries sustainably. However, there is a lack of consensus on how EBFM should be implemented. Different interrelated difficulties, such as understanding well enough the marine ecosystem itself, measuring and monitoring all the relevant variables, and identifying a more accurate set of governance conditions still remain unsolved (Garcia and Staples, 2000; Hayes et al., 2015, 2020). Additionally, despite the overall and increasing demand for practical, interdisciplinary and well-tested decision-making tools to assess resources' management, the fact is that complex questions arise when researches try to evaluate and improve the decision-making process through new sustainability related forms of risk (Guerry et al., 2015; Matthies et al., 2019).

There is a growing branch in the literature that suggests financial approaches be considered in fisheries management (Yang et al., 2008; Gourguet et al., 2014; Pokki et al., 2018). Specifically, researchers in the field of environmental and natural resources have recently advocated applying the modern portfolio theory (MPT) (Markowitz, 1952) to improve the guidance and decision making process of natural resources, including agriculture (Knoke et al., 2015; Matthies et al., 2019), landscape conservation under climate change (Ando and Mallory, 2012; Shah and Ando, 2015), forestry (Knoke and Wurm, 2006; Reeves and Haight, 2000; Matthies et al., 2015), energy (Bazilian and Roques, 2009), biodiversity conservation and crop diversification (Fraser et al., 2005; Paut et al., 2019), and last, but not least, fishing resources (Edwards et al., 2004; Sanchirico et al., 2008; Rădulescu et al., 2010; Jin

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et al., 2016; Alvarez et al., 2017; Carmona et al., 2020; Lopetegui and del Valle, 2020). In fact, there exists a sounded parallelism between financial assets and fish stocks. Fish stocks can be viewed as natural assets capable of generating return flows (Sanchirico et al., 2008, 2020). These returns can be monetary or monetized depending on the nature of the assets or harvestable resources. For example, fish landings can be measured in tonnes or monetized, multiplying the quantity of the landings by their corresponding market values (i.e. prices) as if they were financial assets. Notice also that fishers choose their target species among the diverse and disposable portfolio of fish species.

MPT is based on a standard microeconomic model, where an investor chooses from a variety of available financial assets, with varying rates of return (an economic good) and risk (an economic bad). Conventional examples of financial assets are bonds, stocks, derivatives, futures and swaps (Cvitanic and Zapatero, 2004). These assets are combined, creating this way a financial portfolio with the aim to get the highest expected return at the lowest risk level, taking for granted that the diversification of assets reduces the global risk of portfolios (Kolm et al., 2014). Particularly, MPT proposes diversifying investment options to optimize the portfolio of risky assets using a mean-variance optimization (MVO) model. Thus, for a given level of return, one can derive the minimum risk by minimizing the variance of a portfolio, and find the financial efficient portfolio frontier (FEF) where different efficient portfolios can be selected. Portfolios below the FEF are inefficient, as a better performance can be achieved at the same risk level, or the same performance at a lower risk. Based on the FEFs, alternative efficient portfolios may be proposed depending on the target return and risk levels. For example, the minimum risk portfolio (MRP) could be suggested in order to achieve the lowest possible risk, or the tangency portfolio (TP) to achieve the optimum portfolio with the highest reward, which maximizes the risk/return ratio (also known as Sharpe Ratio (SR) (Sharpe, 1994)).

Using conventional measures such as variance or covariance to proxy risk in the MPT framework involves assuming that returns are normally distributed or that investors have a quadratic utility function (Harlow, 1991). However, there is huge empirical evidence to admit that the distribution of many financial returns is non-normal (Fama and Roll, 1968; Boothe and Glassman, 1987; Sheikh and Qiao, 2009), and that usually returns are fat tailed (Jansen and De Vries, 1991). Additionally, using variance or covariance also involves that gains and losses are equally penalized, and accordingly, neither variance nor covariance would be appropriate risk indicators when portfolio managers are loss averse (Kahneman et al., 1990; Lusk and Coble, 2008). Moreover, MVO fails to identify strategies that minimize risk. As far as investors are more concerned about potential losses from extreme shocks, financial practitioners increasingly have been paying more attention to downside risk measures (Wan et al., 2015). In fact, financial practitioners (Miller and Reuer, 1996; Gundel and Weber, 2007; Zhu et al., 2009; Ling et al., 2014) broadly recommended Conditional Value-at-Risk (CVaR), as a robust and alternative risk indicator. Therefore, Rockafellar et al. (2000), Rockafellar and Uryasev (2002), Alexander and Baptista (2004) and Salahi et al. (2013), instead of using variance or covariance, propose a mean-CVaR portfolio selection model as a non-parametric method to optimize and estimate the FEF.

In the natural resources domain, and specifically in fisheries, there is also place for the variance to measure the risks associated with stock-attribute and other uncertainties (Edwards et al., 2004). For instance, Sethi (2010) analyses risks management practices in use in fisheries and presents strategies focusing on decision analysis, including the concept of risk assessment. Moreover, Alvarez et al. (2017) use variance to measure risk of different strategies to find the actions that optimize the provision of ecosystem service flows. In addition, Privitera-Johnson and Punt (2020) develop a new approach that bases the calculation of scientific uncertainty. Nevertheless, variance would not still be appropriate when decision-makers are concerned with underperformance of a fish portfolio below a certain benchmark level of return (Rom and Ferguson, 1994; Fock et al., 2011), particularly when they aim to prevent uncertain negative outcomes, but do not mind the unexpectedly positive results (Shah and Ando, 2015). Hence, downside risk indicators are proposed as a better alternative to measure a bad or undesired outcome, that is, the worst-case loss (Charles, 1983; Alvarez et al., 2017; Lopetegui and del Valle, 2021).

Moreover, MPT is consistent with an ecosystem-based fisheries management (EBFM) approach that jointly considers multiple fish stocks. Fish species interactions are also implicitly considered by the inclusion of species based revenues and covariances. Accordingly, applying MPT to fisheries management might be useful to improve decision-making and help to specify optimal policies that account for species interactions in an EBFM framework. This marriage between financial and fisheries economics literature is still rather recent, and it provides an attractive framework to face the management of multi-stock population dynamics by suggesting strategies to maximize returns and/or minimize risks.

Although the estimation of FEFs in the fisheries domain follows the same general structure as in finances, however, since fish stocks are limited, it is necessary to include some specific constraints in order to propose sustainable solutions that ensure their future survival (Sanchirico et al., 2008; Alvarez et al., 2017). If we are not including such constraints in the optimisation model, our recommendations might even imply catching up to a level that could lead to the collapse of fish stocks. These additional constraints can limit either, the initial investment and risk preferences (Knoke et al., 2005; Knoke and Wurm, 2006), a desired minimum diversification level (Halpern et al., 2011) and/or a TAC based regulation (Carmona et al., 2020). For the purpose of our study, we are including a compound set of constraints to obtain the financial efficient frontier (FEF). First, following Sanchirico et al. (2008), we include an upper box constraint as the maximum observed weight of each species to ensure that the proposed weights keep under sustainable solutions. Notice that these weights represent the proportion of each fish species to total landings. Second, we add a minimum box constraint. Notice that the mean return of certain species is negative, and accordingly, their related risk level is extremely high. Nevertheless, it would not be feasible to recommend zero catches for these risky fish species, because it would directly imply the closure of these fisheries, which might not be socio-economically sustainable. Thus, with the minimum box constraint, we ensure that our recommendation at least involves the minimum observed proportion to total landings from each fish species. Third, following Carmona et al. (2020), we are also including an upper maximum constraint that measures the weight of the quotas as a percentage to total landings. This further constraint works replacing, for regulated species, the above-mentioned maximum observed weight by their quota weight; while for the non-regulated ones the maximum observed constraint is maintained. This way, the FEF fits reality, keeps under regulatory limits, and reveals a feasible reallocation of landings to achieve the efficient portfolio that minimizes risk for a certain desired level of return. This would be useful to simulate policies that the authorities may want to follow in setting the maximum catch thresholds and observe how policy makers' decisions would affect the reallocation of landings; implying changes in both, return and risk levels. Notice that the above-mentioned constraints are already standard elements in most harvest control rules (HCR). In fact, HCRs reveal policy choices when setting acceptable catch levels, e.g. limits (Kvamsdal et al., 2016).

In the framework of the above-mentioned financial fisheries economics literature, the main objective of this paper is to suggest an efficient redistribution of landings by species within each of the EU fishing countries in the North-East Atlantic EU waters. In order to do so, we estimate their respective FEFs in the risk-return space. Afterwards, we suggest how each individual country could change its species portfolio, either to increase returns, and/or reduce risk. Our contribution to the literature is innovative twofold. Firstly, to the best of our knowledge, this is the first paper applying CVaR in multispecies fisheries. Secondly, we are applying modern portfolio theory (MPT) to a large ecosystem

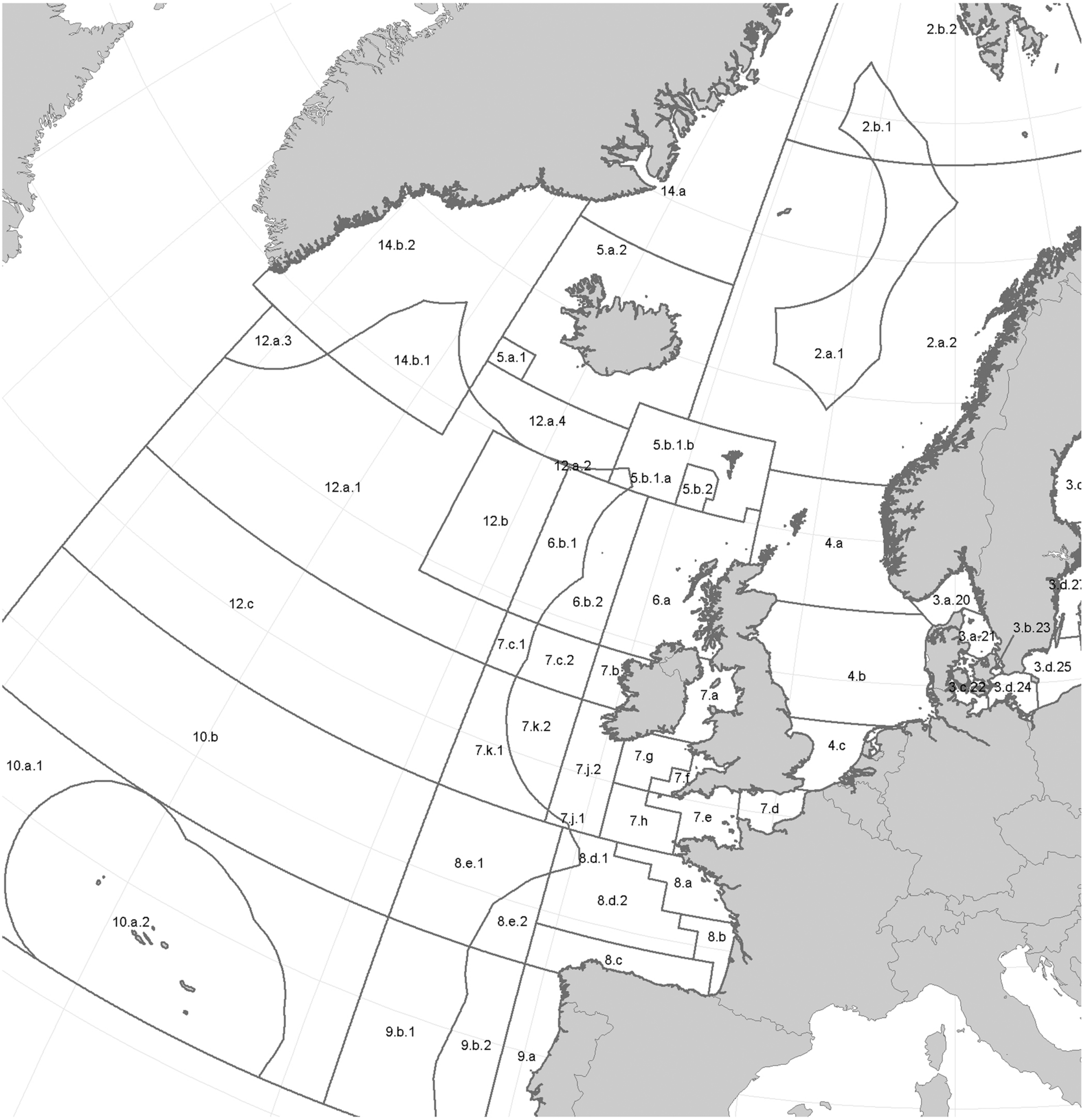

Fig. 1. ICES Areas: North-East Atlantic European waters.
Source: ICES (2019).

comprising the major fishing ground in the EU.

2. Material and methods

2.1. Data

We define the *country-based dynamic fish portfolios* as the group of the main fish species landed in the North-East Atlantic from 2007 to 2018 (see Fig. 1). To generate such portfolios we are using the tonnes live weight (quantity) of the yearly landings (q_{ijt}) {t = 2007,.,2018} of the main fish species {i = 1,.,N′} (thousand tonnes) in each of the countries {j = 1,.,9} (i.e. Belgium, Denmark, France, Germany, Ireland, the Netherlands, Portugal, Spain and United Kingdom)[1] in the target area. Landings data comes from EUROSTAT (2019).

Notice that these country-based fish portfolios could also be defined in terms of the value of landings (€). Undoubtedly, fish prices (p_{ijt}) also give relevant information about the food-related ecosystem services generated by a multispecies fishery (Alvarez et al., 2017). Nevertheless, although the value of landings ($p_{ijt*}q_{ijt}$) a priori seems to be more related to the financial arena, we are using the landed weight (q_{ijt}) for two main

[1] We are excluding Finland and Sweden, because their main fishing area is the Baltic Sea.

Table 1
Fish species selection by country.

Country	Original sample (N_j)	Selected sample (N'_j)	Coverage
Belgium (BE)	70	23	90 %
Denmark (DK)	125	10	92 %
France (FR)	393	44	87 %
Germany (DE)	106	9	88 %
Ireland (IE)	206	20	90 %
The Netherlands (NL)	225	9	89 %
Portugal (PT)	403	26	86 %
Spain (ES)	858	42	83 %
United Kingdom (UK)	214	21	90 %

Notes: Coverage level of the selected species (N'_j) to the total number of species (N_j) landed in each country. N_j is the original sample of species landed, N_j' is the number of species included in the optimization problem (3).

reasons. Firstly, local fisheries are often price takers (Crona et al., 2016; Rosales et al., 2017), that is, they do not control prices because local catches are generally too small, relative to total market supply (Sethi, 2010). Secondly, quotas for individual fish stocks limit the maximum allowable catches (TAC), which are also measured in thousand tonnes live weight. Consequently, our country-based efficient portfolio proposal will be also focused on the potential reallocation of the landings, specifying the fish species that should be targeted to land more or less according to our FEF, so as to land the largest amount of fish with the lowest possible risk, regardless of prices, and under sustainable limits.

There are some outstanding asymmetries among countries relative to their species richness (N) that conditioned the species selection and inclusion approach when calculating the country-based fish portfolios. Some countries, such as Spain (N_{ES}=858) and France (N_{FR}=393), land a huge variety of species, while others, as for example Belgium (N_{BE}=70) and Germany (N_{DE}=106), concentrate their landings in just a few. The concentration of landings is very high in Germany, where the dominant species, Atlantic herring (HER), represents on average 44 % of the total fish landed in the country. The landings in other countries are much more diverse. This is for example the case of France and Spain, where their respective five key leading species barely amount for the 34 % and 39 %. Under this asymmetric distribution of landings across countries, and in order to operate with a computationally tractable optimisation problem to obtain the FEFs, we have established a species inclusion criterion. Our species inclusion criterion satisfies two conditions. Firstly, the aggregated sum of the species included should represent at least 80 % of total landings in that country. Secondly, in order to be included, the species should individually represent at least 1 % of the landings in that country. Thus, following both the criteria, we have removed redundant species that add nothing, but made impossible to run effective calculations to obtain the FEFs. Table 1 summarises the coverage level of the included species (N'_j) to the total number of species landed in each of the nine countries (N_j). Consequently, our country-based efficient portfolio proposal also will be focused on the potential reallocation of landings, specifying the species (N'_j) that should be targeted to land more or less according to our findings.

2.2. Financial Modern Portfolio Theory (MPT) in a nutshell

Fish species (i) are considered as natural assets, whose landings change over the time (t). Fishers must choose their target species from the diverse and disposable portfolio of catchable fish species, each one with a specific risk and return level.[2] Depending on the expected returns and the variability of such returns (or risk), fishers decide their fish species portfolio subject to each species TACs. To proxy the returns (R_{ijt}) (1), we use the yearly change of landings.

$$R_{ijt} = \ln\frac{q_{ijt}}{q_{ijt-1}} = \ln \quad q_{ijt} - \ln \quad q_{ijt-1} \tag{1}$$

where q_{ijt} are the yearly (t) landings of the (i) fish species in country (j). Thus, positive returns (R_{ijt}>0) imply that the landings of the fish species (i) in country (j) has increased, zero returns (R_{ijt}=0) denote that the landings have remained constant, and negative returns (R_{ijt}<0) evidence that the landings have decreased.

FEFs focus on both, returns (R_{ijt}) and their variability or risk. Although the variance (σ^2)[3] of the returns is a widely used indicator to proxy the risk (or variability of species' returns) (see Sanchirico et al., 2008 and Alvarez et al., 2017, among others), there are two main reasons to focus on alternative proxies. On the one hand, when dealing with natural resources, usually their returns are not normally distributed (Dunkel and Weber, 2012; Ando and Mallory, 2012). On the other, the decision-makers tend to be averse to deviations below a benchmark return. Since, under these two circumstances, the variance would not be an appropriate risk measure, environmental and resource economist have increasingly paid special attention on the downside risks indicators (such as VaR or CVaR) (Matthies et al., 2019). In the fisheries domain, downside risk indicators have been also considered to be more appropriate (Charles, 1983; Fock et al., 2011; Alvarez et al., 2017), mainly because fish returns usually follow a skewed distribution and it is often assumed that fishermen are risk averse (Holland, 2010).

Following Rockafellar et al. (2000), Rockafellar and Uryasev (2002) among others, we will focus on the *CVaR* to proxy the variability of the fish species returns or risk, mainly because CVaR is robust to the non-normality of returns, it leads to more effective frontiers to face risk management. CVaR can reduce more risk than the traditional mean-variance optimization approach, which underestimates the tail risk (Wan et al., 2015). CVaR is also a better alternative than the so-called *Value-at-Risk (VaR),*[4] which fails to satisfy some essential properties such as coherence[5] (Jorion, 2001; Alexander and Baptista, 2004; Guo et al., 2019). Specifically, CVaR measures the conditional expectation of losses exceeding the α-quantile of the return (R_{ijt}) (1) distribution at a specified confidence level (α) (2), that is to say, the average worst-case loss. Thus, CVaR averages all the fish returns (1) in the distribution worse than the α-quantile.

$$\mathrm{CVaR}(R_{ij}) = -E\left[R_{ijt} \middle| -R_{ijt} \leq -q_\alpha(R_{ijt})\right] \tag{2}$$

where α is the confidence level $\alpha\epsilon(0,1)$ and q_α is the α-quantile of the return's distribution (R_{ijt}) (1) (Emmer et al., 2015). Following the latest revisions of the Basel Committee, we will also use a confidence level of 97.5 % (Basel III, 2013). Notice that CVaR ranges from 0 to 1. The lowest risk (CVaR=0) means that in the worst case, the quantity of fish landed keeps constant (R_{ijt}=0). The highest risk (CVaR=1) implies that in the worst case, the landings would be reduced almost by 100 % (R_{ijt} =−1).

Based on returns (R_{ijt}) (1) and risk (CVaR) (2), we suggest the next mean-CVaR optimization problem to find the constrained financial efficient frontier (FEF_j) for each of the nine EU fishing countries (j) in the target area. Solving (3) subject to (3.1. and 3.2), we will obtain the constrained FEF or minimum risk (CVaR) set of fish portfolios. That is to say, the optimal weights (%) that minimize the total risk (CVaR) of the country's fish portfolio (w_{ij}*) that gives the efficient combination of fish species for each of the nine EU countries.

[2] In general, as it is in the financial arena, there is a negative tradeoff between the expected returns and the risk of the fish species. Higher expected returns assume more risk, and, contrarily, lower expected returns are associated with lower risk.

[3] Variance: $\sigma^2_{ij} = \sum_{t=1}^{n} \frac{(R_{ijt}-\overline{R}_{ij})^2}{n-1}$.

[4] Value-at-Risk (VaR) measures the worst expected loss over a given horizon under normal conditions at a given level of confidence (Jorion, 2001).

[5] A risk measure is coherent when it satisfies the properties of monotonicity, sub-additivity, homogeneity, and translational invariance. (See Artzner et al. (1999) for further details on the underlying four axioms).

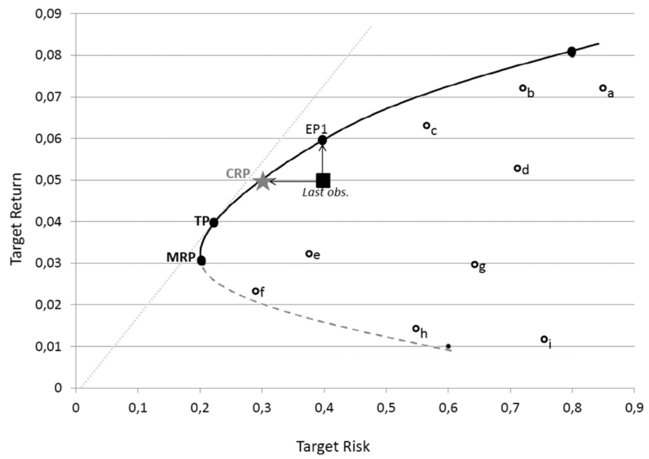

Fig. 2. Theoretical FEF. *Notes*: The curved line constitutes a theoretical FEF. Any point at the downer the convex grey curve, is an inefficient portfolio, and any point the concave black part is an efficient one. The downer black point is the minimum risk portfolio (MRP), the next black point is the tangency portfolio (TP), black box is the last observed landings distribution, and the grey star is the constant return portfolio (CRP).

$$\min_{w} \mathrm{CVaR}\left(w_{ijt}\right) \tag{3}$$

$$s \cdot t \cdot E(R_{jt}) \geq M_{jt} \tag{3.1}$$

$$w_{ij}^{min} \leq w_{ijt} \leq w_{ij}^{quota} \tag{3.2}$$

where w_{ijt}[6] are the landings' weights for the fish species (i) in country (j) at time (t), that is the portion of each fish species to total landings, and CVaR(w_{ijt}) is the risk of the fish portfolio. The constraint (3.1) ensures that the expected return of the fish portfolio ($E(R_{jt})$)[7] is higher than the target return (M_{jt}). The constraint (3.2) is the box constraint, which ensures that each weight (w_{ijt}) is higher than the minimum observed weight (w_{ij}^{min}) and lower than the maximum allowed weight (w_{ij}^{quota}) ,[8] that is the maximum weight of the quotas as a percentage to total landings.

The strategy to model the constrained FEF_j is as follows: firstly, using the fish landings (in thousand tonnes) we measure the returns (R_{ijt}) (1). Secondly, in order to guide the choice of the most appropriate risk indicator to be used in the optimization model (3), we analyse the distribution of the returns (R_{ijt}), paying special attention to check their empirical distributional properties. Since, as expected, returns do not follow a normal distribution, we opt for $CVaR_{ij}$ (2) as the most appropriate risk indicator for the FEF_j estimation. Thirdly, once the returns (R_{it}) (1) and risk (CVaR) (2) are calculated, we design the mean-CVaR portfolio selection model (3) to estimate the FEF_j for each country (j) so as to optimize country level portfolios of harvestable fish species. Based on each FEF_j, we will be able to analyse whether the current fish portfolios of each country are financially efficient or not, and, potentially, recommend an efficient reallocation of their landings that result in the lowest level of risk for a given expected level of return. We are taking advantage of the *fPortfolio* package from R software (Wuertz et al., 2017; R Core Team, 2018).

Fig. 2 illustrates a theoretical example of a FEF curve. The target return is on the y axis and risk is captured along the x axis. Individual fish species' (such as a,b,c,d,e,f,g,h,i) risk vs. return points are shown. In a portfolio, fish species are combined and the FEF curve is revealed. The concave black curve is the efficient FEF, and any point at the FEF represents an efficient combination of fish species, in order to get the minimum risk for a certain level of return. The convex and grey lower part of the curve is the inefficient frontier. Any point there has a respective efficient point with a higher return for the same risk level. Portfolios, which are not on the FEF, are also inefficient. That is the case of the last observed distribution of fish landings (black box). Accordingly, it is possible to redistribute fish species and achieve a better risk-return performance. For instance, we would suggest the constant return portfolio (CRP), as a better alternative to keep the same rate of return, but considerably reduce risk. Alternatively, the rate of return could be also increased to an efficient portfolio (EP1) keeping risk constant. The lowest point at the efficient FEF is the minimum risk portfolio (MRP). This portfolio shows the efficient combination of fish species that leads to the lowest risk level. The tangency line starts from the zero risk-free rate and touches the FEF frontier curve at the tangency portfolio (TP) point. The TP is the optimum portfolio with the highest reward, where the risk/return ratio also known as Sharpe Ratio (SR), is maximized.

3. Results

Fig. 3 illustrates the distribution of the mean returns ($\overline{R}_{ij}$) for each individual country, that is to say, the average increase (positive return ($R_{ijt}>0$)) or decrease (negative return ($R_{ijt}<0$)) of landings. Two major points should be highlighted. First, it can be observed a quite heterogeneous distribution of the returns among countries. Second, as expected, the returns do not follow a normal distribution (see Shapiro-Wilks normality tests results in Table 2). Accordingly, neither the variance nor Value-at-Risk (VaR) would be appropriate risk indicators, because they both assume that returns follow a normal distribution. Therefore, we confirm that CVaR is the most appropriate and robust risk indicator.

The optimisation problem (3), including the minimum constraint (3.1), the quota constraint for the TAC-based regulated species and maximum constraint for the resulting non-regulated species (3.2), yields the constrained efficient frontier (FEF_j). The FEF_j curves for each individual country (Fig. 4) include the target return on the y axis, and risk on the x axis. Thus, each curved line constitutes the FEF_j, where the convex grey points are inefficient portfolios, and the concave black points efficient ones. Each efficient portfolio (black point) in the curve is an efficient combination of fish landings to get the minimum risk for a certain level of return. The lowest point at the FEF_j (downer black point), is the minimum risk portfolio (MRP), which shows the efficient combination of species that leads to the lowest possible risk (CVaR). Each of the country-based FEF_j also include the portfolio for the last observed distribution in 2018 (black box), and our optimum efficient portfolio proposal (grey star).

Our proposal is regarded as an efficient and feasible reallocation of landings, where a new weighting scheme is recommended. These proposals refer to the weight (w_{ij}*) that each fish species should have to achieve the target risk and return levels. Broadly speaking, there are three types of efficient portfolio proposals depending on the particularities of each individual country. First, we suggest tangency portfolio (TP) for the countries in which the efficient portfolio tangency exists and, at least, reaches the last observed (2018) return level. This combination of species (TP) would lead to the optimum scenario where the

[6] Landings weights: $w_{ijt} = \frac{Landings_{ijt}}{\sum Landings_{ijt}}$.

[7] $E(R_{jt}) = \sum_{i=1}^{N} w_{ijt} * \overline{R}_{ij}$, reflects the overall mean return for all species included in the fish portfolio.

[8] Notice that, for the TAC based (k) fish species, we have included the quota constraint (w_{ij}^{quota}), whereas for the non-regulated (N-k) fish species we have considered the maximum observed weight constraint (w_{ij}^{max}).

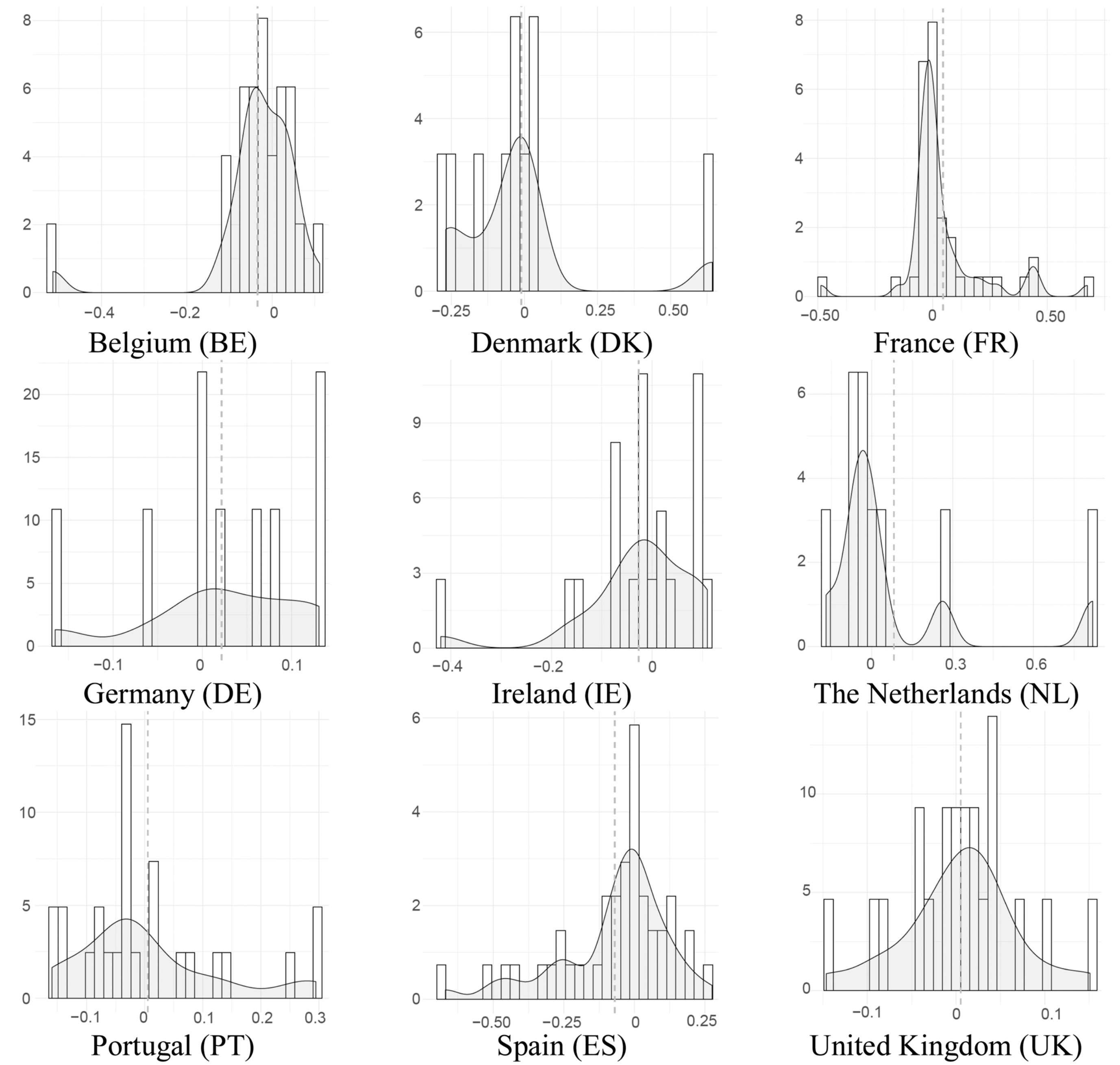

Fig. 3. Country-based histograms of the mean returns ($\overline{R}_{ij}$).

Table 2
Shapiro-Wilk normality test.

Country	W	P-value
Belgium	0.808	3.8E-16
Denmark	0.674	1.4E-13
France	0.690	<2.2e-16
Germany	0.592	1.9E-14
Ireland	0.603	<2.2e-16
The Netherlands	0.764	1.0E-10
Portugal	0.830	3.6E-16
Spain	0.763	<2.2e-16
United Kingdom	0.817	5.6E-15

Notes: Shapiro-Wilk normality test for yearly landings returns (R_{ijt}) by country (j).
P-values: *** significant at 1 %, ** significant at 5 %, * significant at 10 %. If p-value is equal or less than 0.01, then the hypothesis of normality will be rejected.

highest risk-reward ratio is obtained. Second, if the TP does not exist[9] or the TP return does not reach the last observed return level, we suggest a second-best strategy. Namely, the minimum risk portfolio (MRP), that is to say, the efficient combination of fish species that leads to the lowest possible risk level. Third, if neither TP nor MRP reach the last observed return level, in that case, as third-best strategy we suggest the Constant Return Portfolio (CRP), which is the efficient portfolio that at least

[9] There are two main reasons for the lack of TP. First, in the case of some countries, most of the fish species have rather low or even negative mean returns, which considerably reduces possible efficient combinations of fish species. Second, as we are including such constraints, we are also adding extra limitations to all the possible efficient combinations. Thus, in some countries the FEF_j curve and the possible efficient combinations is much more reduced than in other countries.

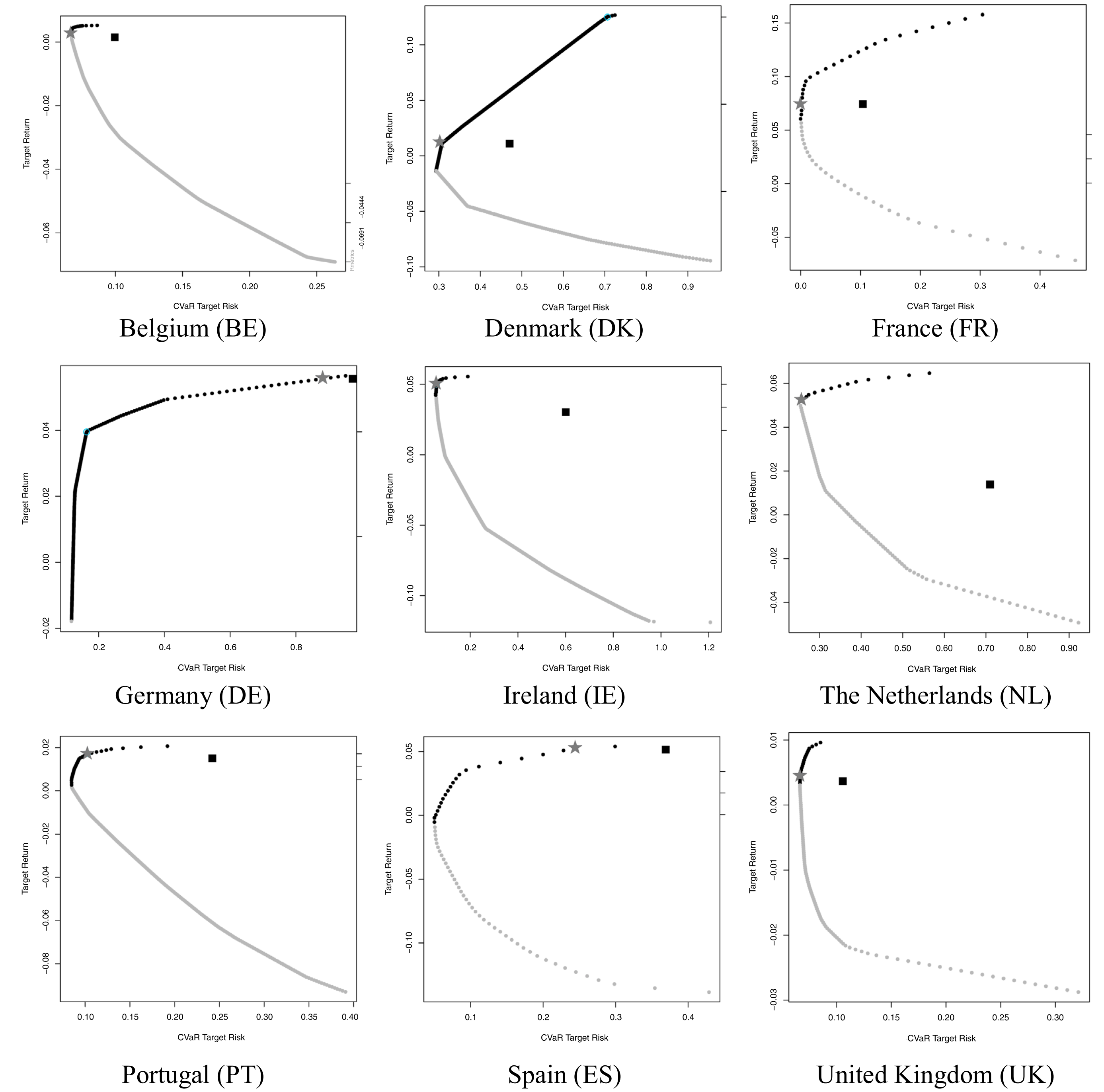

Fig. 4. Constrained FEFs by country. *Notes*: Each curved line constitutes a FEF. The convex grey points are inefficient portfolios, and the concave black points efficient ones. Each black point in the curve is an efficient combination of fish landings to get the minimum risk for a certain level of return. The downer black point is the minimum risk portfolio, which shows the efficient combination of species that leads to the lowest possible risk. The black box is the last observed landings distribution, and the grey stars are our optimum efficient portfolio proposals.

reaches the last observed (2018) return. Tables 4–12 on appendix capture the observed and suggested portfolios for each individual country and their respective last observed weights (w_{ijt}) and the suggested efficient weights (w_{ij}*). Following our proposal, countries could achieve an efficient distribution of fish landings that increases or, at the worst, maintains constant the observed return, and significantly reduces risk.

3.1. *Constrained financial efficient frontiers for individual countries*

3.1.1. *Belgium*

The number of fish species satisfying the inclusion criterion in Belgium reaches 23 (N'_{BE}=23). The most outstanding species, i.e. European plaice (PLE),[10] constitutes on average the 26 % of total landings, and the five key leading fish species, concentrate the 54 %. The leading species, i.e. European plaice (PLE), was at least 23.25 % and as much 35.22 % from total landings. Moreover, PLE has a low but positive mean return ($\overline{R}_{PLE,BE}$=0.02), low risk ($CVaR_{PLE,BE}$=0.15) and potential to increase its landed weight up to 45.68 %, as maximum allowed weight by

[10] Notice that we are using the 3-alpha identifier. The complete list of names may be found on Table 13 on appendix.

Table 3
Key efficiency gains from the last observed portfolio to the efficient portfolio proposal.

Country	Portfolio	Strategy	Return ($\overline{R}_j$)	Risk ($CVaR_j$)	Δ Return	∇ Risk
Belgium	Last Obs.		0.001	0.101	–	–
	Proposal	MRP	0.003	0.067	+181 %	-34.02 %
Denmark	Last Obs.		0.014	0.47	–	–
	Proposal	TP	0.014	0.32	const.	-33.41 %
France	Last Obs.		0.07	0.107	–	–
	Proposal	CRP	0.07	0.002	const.	-97.98 %
Germany	Last Obs.		0.056	1	–	
	Proposal	CRP	0.056	0.91	const.	-8.42 %
Ireland	Last Obs.		0.033	0.62	–	–
	Proposal	TP	0.05	0.06	+52.10 %	-90.39 %
The Netherlands	Last Obs.		0.015	0.71	–	–
	Proposal	MRP	0.051	0.28	+239.51 %	-61.22 %
Portugal	Last Obs.		0.015	0.24	–	–
	Proposal	TP	0.017	0.1	+11.92 %	-57.13 %
Spain	Last Obs.		0.051	0.38	–	–
	Proposal	CRP	0.051	0.23	const.	-39.65 %
United Kingdom	Last Obs.		0.003	0.11	–	–
	Proposal	CRP	0.003	0.07	const.	-40.28 %

Notes: Summary of the last observed distribution (Last Obs.) and our efficient proposal (w_{ij}*) by country. Strategy refers to the type of efficient portfolio we are suggesting: the tangency portfolio (TP), the minimum risk portfolio (MRP) or the constant return portfolio (CRP). $\overline{R}_j$ is the overall mean return of the fish portfolio, $CVaR_j$ is the overall risk, Δ Return is the increase over the last observed return, ∇ Risk is the risk decrease over the last observed risk.

Table 4
Landings return, risk and specific weights for Belgium.

Species	$\overline{R}_{ij}$	$CVaR_{ij}$	w_{ij}^{min}	w_{ij}^{max}	w_{ij}^{quota}	Last Obs. (w_{ijt})	w_{ij}*
PLE	0.02	0.15	23.25 %	35.22 %	45.68 %	33.68 %	29.93 %
SOL	-0.05	0.21	12.15 %	22.41 %	23.07 %	12.15 %	12.15 %
COD	-0.07	0.88	2.76 %	5.92 %	7.66 %	2.99 %	2.76 %
LEM	-0.03	0.36	3.11 %	5.25 %	–	3.26 %	3.11 %
CTC	-0.05	0.98	1.85 %	7.19 %	–	5.48 %	1.85 %
GUU	0.05	0.23	2.16 %	6.91 %	–	6.91 %	6.91 %
CNZ	0.11	0	1.03 %	3.91 %	–	3.78 %	3.91 %
DGZ	0.01	0	2.46 %	3.29 %	–	3.18 %	3.19 %
RJC	-0.03	0.38	2.24 %	3.50 %	–	2.41 %	2.24 %
SCE	-0.06	0.22	2.13 %	3.55 %	–	2.13 %	2.13 %
SCL	-0.11	1	1.01 %	3.74 %	–	1.01 %	1.01 %
ANF	0.02	0.47	1.68 %	3.39 %	20.14 %	3.16 %	7.07 %
SYC	0.04	0	2.00 %	3.51 %	–	3.51 %	3.51 %
RJH	0.04	0.18	1.50 %	3.28 %	–	2.82 %	3.28 %
CSH	0	0.47	1.48 %	3.15 %	–	2.16 %	3.15 %
TUR	0.03	0.14	1.66 %	2.70 %	2.11 %	2.70 %	2.11 %
BIB	-0.05	0.31	1.39 %	2.85 %	–	1.79 %	2.21 %
SKA	-0.51	1	0.05 %	9.29 %	–	0.07 %	0.05 %
DAB	-0.1	0.46	0.86 %	2.69 %	–	0.86 %	0.86 %
LEZ	0.06	1	0.84 %	3.37 %	3.19 %	2.10 %	3.19 %
BLL	-0.03	0.15	1.33 %	1.89 %	–	1.67 %	1.33 %
GUR	-0.02	0.47	0.98 %	1.99 %	–	1.53 %	1.99 %
FLE	-0.05	0.71	0.65 %	1.96 %	–	0.65 %	1.96 %
					Overall Return ($\overline{R}_j$)	**0.001**	**0.003**
					Δ Return	–	(+181 %)
					Overall Risk ($CVaR_j$)	**0.101**	**0.067**
					∇ Risk	–	(−34.02 %)

Notes: Landings mean returns ($\overline{R}_{ij}$), risk ($CVaR_{ij}$), minimum constraint (w_{ij}^{min}), maximum constraint (w_{ij}^{max}), quota constraint (w_{ij}^{quota}), last observed weight (Last Obs. (w_{ijt})), and suggested efficient weight (w_{ij}*) for each of the fish species (i) and country (j = Belgium). The Overall Return ($\overline{R}_j$) is the overall return of the fish portfolio, Δ Return is the return increase of the efficient portfolio over the last observed distribution, Overall Risk ($CVaR_j$) is the overall risk of the fish portfolio and ∇ Risk is the risk decrease of the efficient portfolio over the last observed distribution.

quota regulation. Nevertheless, our suggestion implies reducing its proportion to 29.93 %, due to its low contribution to increase the mean return. Contrarily, anglerfishes (ANF) has historically never been less than 1.68 % and more than 3.39 % from total landings. Anglerfishes (ANF) also has a positive mean return ($\overline{R}_{ANF,BE}$=0.02), but a higher risk ($CVaR_{ANF,BE}$=0.47). In addition, its quota constraint enables to increase its proportion up to 20.14 %. Therefore, even ANF is riskier than PLE, we recommend increasing its weight to 7.07 %, due to the benefit derived from risk diversification.

Notice that most of the fish species have quite low or even negative mean returns, which considerably reduces the efficient frontier curve (FEF_{BE}) (i.e. possible efficient combinations of fish species) shown in Fig. 4. As far as there is no tangency portfolio (TP), we recommend the minimum risk portfolio (MRP) as the second-best strategy. Our efficient portfolio proposal (grey star) implies the reallocation of fish landings to achieve an efficient portfolio composition at a higher return (+181 %) and lower risk (−34.02 %), compared to the portfolio for the last

Table 5
Landings return, risk and specific weights for Denmark.

Species	$\overline{R}_{ij}$	$CVaR_{ij}$	w_{ij}^{min}	w_{ij}^{max}	w_{ij}^{quota}	Last Obs. (w_{ijt})	w_{ij}*
SPR	0.02	0.38	21.62 %	38.85 %	30.48 %	38.85 %	30.48 %
SAN	-0.15	1	4.89 %	38.91 %	61.63 %	4.90 %	16.99 %
HER	-0.02	0.24	13.18 %	23.07 %	23.11 %	22.45 %	23.11 %
WHB	-0.01	1	0.14 %	18.97 %	6.69 %	18.87 %	6.04 %
MUS	-0.06	0.76	2.70 %	7.31 %	–	4.94 %	7.31 %
NOP	0.64	1	0.00 %	7.11 %	21.50 %	3.85 %	7.04 %
CAP	-0.27	1	0.27 %	5.78 %	0.63 %	0.36 %	0.27 %
BOR	-0.26	1	0.03 %	8.42 %	3.70 %	0.04 %	0.00 %
COD	-0.03	0.27	2.09 %	4.37 %	4.37 %	2.45 %	4.37 %
PLE	0.03	0.1	1.65 %	4.34 %	4.38 %	3.28 %	4.38 %
					Overall Return ($\overline{R}_j$)	**0.014**	**0.014**
					Δ Return	–	(const.)
					Overall Risk ($CVaR_j$)	**0.47**	**0.32**
					∇ Risk	–	(−33.41 %)

Notes: Landings mean returns ($\overline{R}_{ij}$), risk ($CVaR_{ij}$), minimum constraint (w_{ij}^{min}), maximum constraint (w_{ij}^{max}), quota constraint (w_{ij}^{quota}), last observed weight (Last Obs. (w_{ijt})), and suggested efficient weight (w_{ij}*) for each of the fish species (i) and country (j = Denmark). The Overall Return ($\overline{R}_j$) is the overall return of the fish portfolio, Δ Return is the return increase of the efficient portfolio over the last observed distribution, Overall Risk ($CVaR_j$) is the overall risk of the fish portfolio and ∇ Risk is the risk decrease of the efficient portfolio over the last observed distribution.

observed distribution (black box). Thus, we are able to propose a feasible and efficient distribution of fish landings in Belgium. Accordingly, landings would increase by 3 %, and in the worst case, landings would only be reduced by 6.7 %.

3.1.2. Denmark

10 fish species (N'_{DK}=10) satisfy the inclusion criterion in Denmark. The leading fish species, i.e. European sprat (SPR), constitutes on average the 30 % of total landings, and the five key leading fish species, concentrate the 81 %. Based on our results, the most remarkable species are sandeels (SAN) and European sprat (SPR). For example, sandeels (SAN) has a negative mean return ($\overline{R}_{SAN,DK}$=−0.15) and a very high risk ($CVaR_{SAN,DK}$=1). However, our proposal implies increasing its weight from the last observed 4.89 % to the recommended 16.99 %, since other low risk species (i.e. European sprat (SPR) (positive mean return and low risk) and Atlantic herring (HER) (negative but low mean return and also low risk)) have already reached the maximum allowed weights, 30.48 % and 23.11 % respectively. This implies targeting species such as SAN, that might not be attractive from the pure financial point of view, but enable diversifying the fish portfolio and reducing the overall risk (−33.41 %).

The tangency portfolio (TP) is suggested as the best strategy to efficiently redistribute landings. Our proposal keeps the return constant, but reduces risk by 33.41 %, compared to the portfolio for the last observed distribution. By changing the portfolio composition, Denmark could achieve an efficient portfolio that keeps the return, but reduces risk. Accordingly, the average increase of landings would be 1.4 %, and in the worst case, landings would be reduced by 32 %.

3.1.3. France

The number of fish species satisfying the inclusion criterion in France reaches 44 (N'_{FR}=44). The leading species, i.e. Tangle (LQD), constitutes on average the 15 % of total landings, and the five most outstanding fish species, concentrate the 39 %. Historically, European hake (HKE) has never exceeded the 6.10 % of total landings in France. However, HKE has potential to reach the maximum allowed weight of 22.74 %. In addition, HKE has a positive mean return ($\overline{R}_{HKE,FR}$=0.08) and a quite low risk ($CVaR_{HKE,FR}$=0.19), which makes HKE an interesting species from the pure financial point of view. Thus, our proposal implies increasing HKE until it reaches the maximum weight established by the quota regime (22.74 %). On the contrary, European sardine (PIL) has a negative mean return ($\overline{R}_{PIL,FR}$=−0.04) and high risk ($CVaR_{PIL,FR}$=0.73). Accordingly, our proposal implies reducing PIL to the historically observed minimum weight (5.70 %).

The efficient frontier curve (see Fig. 4) is somewhat similar to the one estimated for Spain, but both, the last observed and proposed portfolios are different in the case of France. As a third-best strategy, we suggest the constant return portfolio (CRP) (grey star) that keeps the last observed return constant, but considerably reduces the risk (−97.98 %). Following our suggestion for France, we propose an efficient portfolio in which the mean increase of landings would be 7 %, and in the worst case, landings would be only reduced by 0.2 %. Notice that this result is quite close to zero, implying that we are able to suggest an efficient portfolio for France with almost zero risk.

3.1.4. Germany

In the case of Germany only 9 fish species (N'_{DE}=9) satisfy the inclusion criterion. The most outstanding fish species, i.e. Atlantic herring (HER), constitutes on average 44 % of total landings, and the five key leading fish species, concentrate the 77 %. For example, Greenland halibut (GHL) has historically been 1.01 % as minimum and 2.74 % as maximum. Nevertheless, we suggest increasing GHL up to 9.23 %, as maximum allowed weight by quota regulation. Contrarily, our suggestion also involves reducing Atlantic mackerel (MAC) to 6.34 %. Notice that the mean return of MAC is quite low ($\overline{R}_{MAC,DE}$=0.06), and the risk is very high ($CVaR_{MAC,DE}$=1), which does not make MAC attractive at all from a financial point of view.

The constrained financial efficient frontier for Germany is completely different to the one for Belgium. Due to the risk and return particularities of the fish species landed in Germany, there are much more efficient portfolios to be selected than in the Belgian FEF. Nevertheless, the portfolio for the last observed distribution (black square) has a rather high mean return. Therefore, as third-best strategy, we suggest the constant return portfolio (CRP), that is, the efficient portfolio (grey star) that maintains the return level constant (with respect to the last observed distribution), but reduces risk by 8.42 %.

3.1.5. Ireland

The number of fish species fulfilling the inclusion criterion in Ireland is 20 (N'_{IE}=20). The most outstanding species, i.e. Atlantic mackerel (MAC), constitutes on average the 21 % of total landings, and the five more outstanding species, concentrate the 60 %. Atlantic mackerel (MAC), which is the principal species, was 30.83 % from total landings in 2018. Our major changes imply increasing MAC to 41.22 %, which corresponds to the maximum allowed weight by quota regulation. Conversely, blue whiting (WHB) has positive but low mean return ($\overline{R}_{WHB,IE}$=0.03) and a very high risk ($CVaR_{WHB,IE}$=1). Therefore, our proposal implies reducing WHB to the minimum observed weight (1.42

Table 6
Landings return, risk and specific weights for France.

Species	$\overline{R}_{ij}$	$CVaR_{ij}$	w_{ij}^{min}	w_{ij}^{max}	w_{ij}^{quota}	Last Obs. (w_{ijt})	w_{ij}*
LQD	0.28	0.97	0.65 %	17.15 %	–	10.44 %	4.55 %
PIL	-0.04	0.73	5.70 %	14.16 %	–	8.49 %	5.70 %
SCE	0.02	0.33	6.11 %	9.41 %	–	9.41 %	6.11 %
MON	-0.01	0.12	3.30 %	6.23 %	–	4.38 %	6.23 %
HKE	0.08	0.19	2.66 %	6.10 %	22.74 %	5.34 %	22.74 %
MNZ	0.03	0.15	3.53 %	5.10 %	15.58 %	4.62 %	3.53 %
WHE	0.09	0.32	2.13 %	4.74 %	–	4.74 %	2.13 %
MAC	-0.03	0.26	2.50 %	4.37 %	11.42 %	2.87 %	2.50 %
WHG	-0.01	0.27	2.73 %	4.11 %	9.34 %	3.25 %	2.73 %
LAH	0.18	1	0.51 %	10.94 %	–	2.97 %	3.89 %
WHB	-0.04	0.61	0.77 %	5.37 %	15.65 %	3.21 %	5.06 %
CTC	0.67	0.32	0.00 %	4.05 %	–	2.88 %	2.51 %
HOM	-0.01	1	0.81 %	14.83 %	–	1.16 %	0.81 %
POK	-0.15	0.7	0.85 %	5.63 %	25.71 %	0.99 %	0.85 %
COD	0.02	0.91	1.30 %	3.05 %	5.59 %	2.88 %	1.30 %
SOL	-0.04	0.28	1.35 %	2.72 %	4.51 %	1.69 %	1.35 %
HAD	0	0.37	1.06 %	3.18 %	6.66 %	1.45 %	1.06 %
ANE	0	0.57	0.90 %	2.58 %	1.19 %	1.54 %	1.19 %
CRE	0	0.33	1.08 %	2.09 %	–	1.35 %	1.08 %
SQC	-0.01	0.15	1.18 %	2.22 %	–	1.56 %	2.22 %
SQZ	0.45	0.36	0.02 %	2.01 %	–	1.77 %	2.01 %
SYC	-0.04	0.63	1.04 %	2.05 %	–	1.32 %	1.04 %
BSS	-0.06	0.42	0.71 %	1.98 %	–	0.95 %	0.71 %
COE	-0.03	0.65	1.03 %	2.15 %	–	1.41 %	1.03 %
SCR	0.1	0.17	0.88 %	2.17 %	–	2.17 %	2.17 %
BIB	-0.02	0.27	0.78 %	1.81 %	–	1.21 %	0.78 %
HER	-0.01	0.92	0.76 %	2.24 %	17.43 %	0.92 %	0.76 %
YFT	0.14	1	0.04 %	10.77 %	–	0.56 %	0.04 %
NEP	-0.03	0.68	0.81 %	1.80 %	6.04 %	1.29 %	0.81 %
ALB	0.03	0.68	0.36 %	2.23 %	4.11 %	1.38 %	0.36 %
SKJ	0.44	1	0.00 %	9.75 %	–	1.13 %	1.46 %
GKL	-0.01	1	0.45 %	1.80 %	–	1.43 %	0.45 %
BRB	-0.07	0.52	0.58 %	1.74 %	–	0.79 %	0.58 %
POL	-0.06	0.41	0.65 %	1.28 %	7.57 %	0.65 %	0.65 %
GUR	0.05	0.33	0.45 %	1.28 %	–	0.92 %	1.28 %
QSC	-0.01	1	0.16 %	2.18 %	–	1.80 %	2.18 %
SWX	0.05	1	0.05 %	2.79 %	–	0.78 %	1.41 %
SDV	0	0.42	0.66 %	1.11 %	–	0.88 %	0.66 %
LIN	-0.06	0.84	0.44 %	1.08 %	2.01 %	0.44 %	0.44 %
PLE	-0.01	0.3	0.55 %	1.06 %	2.18 %	0.71 %	0.55 %
RJN	-0.02	0.2	0.55 %	0.95 %	–	0.69 %	0.55 %
CTL	-0.49	1	0.02 %	5.86 %	–	0.04 %	0.02 %
MUR	0.42	0.55	0.01 %	1.52 %	–	0.67 %	1.52 %
MEG	0.22	0.13	0.10 %	1.04 %	–	0.89 %	1.04 %
					Overall Return ($\overline{R}_j$)	**0.07**	**0.07**
					Δ Return	–	(const.)
					Overall Risk ($CVaR_j$)	**0.107**	**0.002**
					∇ Risk	–	(−97.98 %)

Notes: Landings mean returns ($\overline{R}_{ij}$), risk ($CVaR_{ij}$), minimum constraint (w_{ij}^{min}), maximum constraint (w_{ij}^{max}), quota constraint (w_{ij}^{quota}), last observed weight (Last Obs. (w_{ijt})), and suggested efficient weight (w_{ij}*) for each of the fish species (i) and country (j = France). The Overall Return ($\overline{R}_j$) is the overall return of the fish portfolio, Δ Return is the return increase of the efficient portfolio over the last observed distribution, Overall Risk ($CVaR_j$) is the overall risk of the fish portfolio and ∇ Risk is the risk decrease of the efficient portfolio over the last observed distribution.

%).

Although the shape and the slope of the Irish efficient frontier curve are quite similar to the Belgian (see Fig. 4), however, the observed and proposed portfolios change considerably. In the case of Ireland, the portfolio for the last observed distribution (black square) has higher risk but lower mean return. Therefore, we suggest the tangency portfolio (TP) as the efficient portfolio proposal (grey star). Consequently, based on to the optimal reallocation of landings, we are able to suggest an efficient portfolio for Ireland that increases return (+52.10 %) and reduces risk (−90.39 %) considerably. Following our proposal, the mean increase of landings in Ireland would be 5 %, and in the worst case, fish landings would be only reduced by 6 %.

3.1.6. *the Netherlands*

Only 10 fish species satisfy the inclusion criterion in the Netherlands (N'_{NL}=9). The outstanding species, i.e. Atlantic herring (HER), constitutes on average the 28 % of total landings, and the five key fish species, concentrate the 81 %. For example, HER was 32.07 % of total landings in 2018, and blue whiting (WHB) was 25.54 %. Our efficient portfolio proposal suggests reducing HER to 26.04 % and WHB to 3.68 %, mainly because both species have a negative mean return and both are risky species. Contrarily, we recommend increasing Atlantic horse mackerel (HOM) from 6.24 % to 10.2 %, jack and horse mackerels (JAX) from 3.50 % to 20.69 % and European plaice (PLE) from 6.79 % to 11.39 %. In addition, common shrimp (CSH) has a low but positive mean return ($\overline{R}_{CSH,NL}$=0.03) and a slightly low risk ($CVaR_{CSH,NL}$=0.31), therefore, we suggest increasing its weight to 7.47 %, coinciding with the maximum observed weight. Contrarily, we propose reducing Atlantic mackerel (MAC) to the minimum observed 7.59 %, since MAC has a negative mean return ($\overline{R}_{MAC,NL}$=−0.04) and high risk ($CVaR_{MAC,NL}$=0.76).

The shape of the FEF for the Netherlands is similar to the Irish FEF,

Table 7
Landings return, risk and specific weights for Germany.

Species	$\overline{R}_{ij}$	$CVaR_{ij}$	w_{ij}^{min}	w_{ij}^{max}	w_{ij}^{quota}	Last Obs. (w_{ijt})	w_{ij}*
HER	0.02	0.24	41.06 %	55.37 %	48.09 %	41.06 %	41.06 %
CSH	-0.06	0.62	4.23 %	19.29 %	–	4.23 %	4.23 %
MUS	0.13	0.86	4.22 %	17.50 %	–	12.86 %	17.50 %
HOM	0	0	4.24 %	8.90 %	–	4.24 %	4.24 %
COD	-0.16	1	0.88 %	9.68 %	13.72 %	0.88 %	0.88 %
MAC	0.06	1	0.08 %	12.34 %	29.71 %	12.34 %	6.34 %
WHB	0.13	1	0.01 %	20.73 %	15.42 %	20.73 %	14.40 %
SAA	0	0	2.13 %	4.47 %	–	2.13 %	2.13 %
GHL	0.08	0.3	1.01 %	2.74 %	9.23 %	1.53 %	9.23 %
					Overall Return ($\overline{R}_j$)	**0.056**	**0.056**
					Δ Return	–	(const.)
					Overall Risk ($CVaR_j$)	**1**	**0.91**
					∇ Risk	–	(−8.42 %)

Notes: Landings mean returns ($\overline{R}_{ij}$), risk ($CVaR_{ij}$), minimum constraint (w_{ij}^{min}), maximum constraint (w_{ij}^{max}), quota constraint (w_{ij}^{quota}), last observed weight (Last Obs. (w_{ijt})), and suggested efficient weight (w_{ij}*) for each of the fish species (i) and country (j = Germany). The Overall Return ($\overline{R}_j$) is the overall return of the fish portfolio, Δ Return is the return increase of the efficient portfolio over the last observed distribution, Overall Risk ($CVaR_j$) is the overall risk of the fish portfolio and ∇ Risk is the risk decrease of the efficient portfolio over the last observed distribution.

Table 8
Landings return, risk and specific weights for Ireland.

Species	$\overline{R}_{ij}$	$CVaR_{ij}$	w_{ij}^{min}	w_{ij}^{max}	w_{ij}^{quota}	Last Obs. (w_{ijt})	w_{ij}*
MAC	0.09	0.19	11.88 %	30.83 %	41.22 %	30.83 %	41.22 %
JAX	-0.02	1	2.49 %	17.60 %	21.79 %	8.17 %	2.49 %
WHB	0.03	1	0.63 %	22.82 %	–	19.49 %	1.42 %
HER	-0.07	0.37	5.28 %	11.00 %	17.25 %	5.28 %	5.28 %
FIN	-0.42	1	0.07 %	18.65 %	–	0.09 %	0.07 %
HKE	0.08	1	0.89 %	9.73 %	–	6.57 %	9.73 %
HOM	0.11	1	0.60 %	10.18 %	–	2.21 %	8.43 %
BOC	-0.02	0.16	3.19 %	5.64 %	–	3.37 %	5.64 %
CRE	-0.16	1	1.70 %	11.87 %	–	2.46 %	1.70 %
MOL	-0.15	0.99	1.36 %	6.77 %	–	1.53 %	1.36 %
MON	-0.07	0.73	1.55 %	4.60 %	–	1.55 %	1.55 %
NEP	0.01	0.36	1.94 %	4.13 %	4.29 %	2.49 %	4.29 %
BOR	-0.07	1	0.02 %	6.58 %	28.69 %	2.80 %	0.52 %
ANF	0.09	0	1.27 %	3.81 %	–	3.81 %	3.81 %
WHG	0.01	0.69	1.06 %	3.07 %	2.63 %	2.10 %	1.40 %
SPR	-0.04	0.78	0.93 %	4.15 %	–	0.93 %	2.01 %
HAD	-0.01	0.44	1.02 %	2.37 %	2.17 %	1.17 %	1.02 %
MNZ	0	0.93	0.84 %	3.74 %	–	2.03 %	3.74 %
LEZ	0.09	0.11	0.67 %	2.54 %	–	2.13 %	2.54 %
WHE	-0.03	0.25	0.97 %	1.77 %	–	0.97 %	1.77 %
					Overall Return ($\overline{R}_j$)	**0.033**	**0.05**
					Δ Return	–	(+52.10 %)
					Overall Risk ($CVaR_j$)	**0.62**	**0.06**
					∇ Risk	–	(−90.39 %)

Notes: Landings mean returns ($\overline{R}_{ij}$), risk ($CVaR_{ij}$), minimum constraint (w_{ij}^{min}), maximum constraint (w_{ij}^{max}), quota constraint (w_{ij}^{quota}), last observed weight (Last Obs. (w_{ijt})), and suggested efficient weight (w_{ij}*) for each of the fish species (i) and country (j = Ireland). The Overall Return ($\overline{R}_j$) is the overall return of the fish portfolio, Δ Return is the return increase of the efficient portfolio over the last observed distribution, Overall Risk ($CVaR_j$) is the overall risk of the fish portfolio and ∇ Risk is the risk decrease of the efficient portfolio over the last observed distribution.

but the main difference comes from the portfolio of the last observed distribution (black square), which has a high risk and low return. As second-best strategy, our proposal (grey star) is the minimum risk portfolio (MRP), which is the combination of fish species that increases the return by 239.51 % and reduces risk by 61.22 %. According to our proposal, the mean increase of landings in the Netherlands would be 5.1 %, and in the worst case, landings would be reduced by 28 %.

3.1.7. Portugal

The number of fish species satisfying the inclusion criterion in Portugal is 26 (N'_{PT}=26). The outstanding fish species, i.e. Atlantic horse mackerel (HOM), constitutes on average the 28 % of total landings, and the five most landed fish species, concentrate the 60 %. European sardine (PIL) and Atlantic chub mackerel (VMA) have negative mean returns ($\overline{R}_{PIL,PT}$=−0.15, $\overline{R}_{VMA,PT}$=−0.01) and rather high risks ($CVaR_{PIL,PT}$=0.57, $CVaR_{VMA,PT}$=0.51). Accordingly, our proposal implies reducing their proportion to the minimum observed weight (respectively 11.38 % and 10.15 %). Contrariwise, Atlantic horse mackerel (HOM) has positive mean return ($\overline{R}_{HOM,PT}$=0.07) and low risk ($CVaR_{HOM,PT}$=0.14). Thus, our proposal suggests increasing its weight to the maximum observed 18.60 %.

The shape of the FEF_{PT} for Portugal is slightly similar to the Spanish FEF_{ES}. The main difference is the efficient portfolio proposal (grey star). We suggest the tangency portfolio (TP) for Portugal, as the best strategy to achieve a higher return (+11.92 %) at a lower risk (−57.13 %), compared to the portfolio for the last observed distribution (black square). This way, the mean increase of landings in Portugal would be 1.7 % and, in the worst case, landings would be reduced by 10 %.

Table 9
Landings return, risk and specific weights for the Netherlands.

Species	$\overline{R}_{ij}$	$CVaR_{ij}$	w_{ij}^{min}	w_{ij}^{max}	w_{ij}^{quota}	Last Obs. (w_{ijt})	w_{ij}*
HER	-0.06	1	22.26 %	35.81 %	27.01 %	32.07 %	26.04 %
WHB	-0.08	1	1.40 %	33.24 %	11.51 %	25.54 %	3.68 %
JAX	-0.17	1	1.04 %	33.42 %	20.69 %	3.50 %	20.69 %
MAC	-0.04	0.76	7.59 %	21.08 %	12.00 %	15.22 %	7.59 %
PLE	0	0.35	4.15 %	12.81 %	11.39 %	6.79 %	11.39 %
CSH	0.03	0.31	1.08 %	7.47 %	–	2.50 %	7.47 %
HOM	0.82	0.23	0.00 %	10.23 %	–	6.25 %	10.23 %
PIL	0.26	1	0.26 %	9.19 %	–	6.20 %	9.04 %
SOL	-0.02	0.15	1.43 %	3.52 %	3.86 %	1.94 %	3.86 %
					Overall Return ($\overline{R}_j$)	**0.015**	**0.051**
					Δ Return	–	(+239.51 %)
					Overall Risk ($CVaR_j$)	**0.71**	**0.28**
					∇ Risk	–	(−61.22 %)

Notes: Landings mean returns ($\overline{R}_{ij}$), risk ($CVaR_{ij}$), minimum constraint (w_{ij}^{min}), maximum constraint (w_{ij}^{max}), quota constraint (w_{ij}^{quota}), last observed weight (Last Obs. (w_{ijt})), and suggested efficient weight (w_{ij}*) for each of the fish species (i) and country (j = The Netherlands). The Overall Return ($\overline{R}_j$) is the overall return of the fish portfolio, Δ Return is the return increase of the efficient portfolio over the last observed distribution, Overall Risk ($CVaR_j$) is the overall risk of the fish portfolio and ∇ Risk is the risk decrease of the efficient portfolio over the last observed distribution.

Table 10
Landings return, risk and specific weights for Portugal.

Species	$\overline{R}_{ij}$	$CVaR_{ij}$	w_{ij}^{min}	w_{ij}^{max}	w_{ij}^{quota}	Last Obs. (w_{ijt})	w_{ij}*
PIL	-0.15	0.57	11.38 %	43.87 %	–	14.12 %	11.38 %
VMA	-0.01	0.51	10.01 %	36.04 %	–	17.16 %	10.15 %
HOM	0.07	0.14	5.23 %	18.60 %	–	18.34%	18.60%
OCC	0.01	0.6	2.43 %	7.44 %	–	4.12 %	7.44 %
BSF	-0.03	0.14	2.85 %	4.16 %	–	4.16 %	4.16 %
RED	-0.1	1	1.43 %	6.44 %	7.64 %	2.56 %	3.98 %
BET	-0.03	0.54	1.46 %	5.19 %	5.17 %	2.80 %	5.17 %
JAA	0.01	0.43	1.79 %	4.37 %	–	4.37 %	4.37 %
COD	0.01	0.46	1.71 %	5.62 %	6.86 %	2.83 %	6.86 %
SKJ	-0.16	1	0.69 %	7.49 %	–	1.72 %	0.69 %
BSH	-0.14	1	0.65 %	4.15 %	–	1.44 %	0.65 %
ANE	0.25	1	0.04 %	8.68 %	4.39 %	8.68 %	4.39 %
HKE	-0.03	0.28	1.23 %	2.23 %	4.65 %	1.42 %	4.65 %
COC	0.14	0.77	0.57 %	3.59 %	–	3.59 %	3.59 %
WHB	-0.08	0.71	0.42 %	2.42 %	8.33 %	1.56 %	0.42 %
BIB	-0.03	0.23	1.07 %	1.84 %	–	1.54 %	1.84 %
COE	-0.03	0.14	0.81 %	1.48 %	–	1.12 %	1.48 %
GHL	-0.06	1	0.35 %	1.49 %	1.70 %	0.79 %	0.35 %
ALB	0.29	1	0.08 %	2.45 %	3.90 %	2.44 %	3.90 %
CTC	-0.04	0.29	0.68 %	0.95 %	–	0.73 %	0.95 %
SWO	-0.16	1	0.46 %	2.10%	1.69 %	0.65 %	0.46 %
REB	0.29	1	0.03 %	1.20 %	–	0.76 %	1.20 %
SBR	-0.08	0.4	0.46 %	0.80 %	–	0.55 %	0.46 %
ULO	0.12	0.29	0.19 %	1.33 %	–	1.33 %	1.33 %
SBA	-0.04	0.4	0.41 %	0.76 %	–	0.49 %	0.76 %
RJC	0.08	0.16	0.21 %	0.79 %	–	0.73 %	0.79 %
					Overall Return ($\overline{R}_j$)	**0.015**	**0.017**
					Δ Return	–	(+11.92 %)
					Overall Risk ($CVaR_j$)	**0.24**	**0.1**
					∇ Risk	–	(−57.13 %)

Notes: Landings mean returns ($\overline{R}_{ij}$), risk ($CVaR_{ij}$), minimum constraint (w_{ij}^{min}), maximum constraint (w_{ij}^{max}), quota constraint (w_{ij}^{quota}), last observed weight (Last Obs. (w_{ijt})), and suggested efficient weight (w_{ij}*) for each of the fish species (i) and country (j = Portugal). The Overall Return ($\overline{R}_j$) is the overall return of the fish portfolio, Δ Return is the return increase of the efficient portfolio over the last observed distribution, Overall Risk ($CVaR_j$) is the overall risk of the fish portfolio and ∇ Risk is the risk decrease of the efficient portfolio over the last observed distribution.

3.1.8. Spain

The number of fish species satisfying the inclusion criterion in Spain reaches 42 (N'_{ES}=42). The outstanding species, i.e. skipjack tuna (SKJ), constitutes on average the 15 % of total landings, and the five key leading fish species, concentrate the 39 %. SKJ has a positive mean return ($\overline{R}_{SKJ,ES}$=0.03), but a very high risk ($CVaR_{SKJ,ES}$=1). Nevertheless, we suggest increasing its weight up to 25.11 %. Notice that SKJ is not regulated by TAC/quota regime and therefore, we recommend catching up to the maximum observed weight in our sample period. Similarly, the second key species, i.e. yellowfin tuna (YFT), has also a rather high risk, but its mean return is negative. Therefore, since YFT is not an attractive fish species from a pure financial point of view, we suggest reducing its proportion to the minimum observed weight (1.07 %).

The pattern and the shape of the FEF_{ES} curve is slightly similar to the Danish (FEF_{DK}), although the last observed portfolio composition and our proposal are radically different. As third-best strategy, we suggest the constant return portfolio (CRP), which is an efficient distribution of landings (grey star) that maintains the mean return constant, but

Table 11
Landings return, risk and specific weights for Spain.

Species	$\overline{R}_{ij}$	$CVaR_{ij}$	w_{ij}^{min}	w_{ij}^{max}	w_{ij}^{quota}	Last Obs. (w_{ijt})	w_{ij}*
SKJ	0.03	1	0.92 %	25.13 %	–	20.01 %	25.11%
YFT	-0.01	1	1.07 %	14.96 %	–	8.94 %	1.07 %
PIL	-0.1	0.69	3.51 %	15.70 %	–	3.51 %	3.51 %
HKE	0.06	0.45	2.83 %	6.92 %	5.37 %	5.27 %	5.37 %
VMA	0.08	0.06	3.18 %	8.40 %	–	8.40 %	8.40 %
JAX	-0.09	0.79	1.61 %	8.43 %	9.72 %	2.50 %	1.61 %
ANE	0.19	0.08	0.79 %	7.01 %	5.75 %	6.91 %	5.75 %
SAA	-0.25	1	0.38 %	9.88 %	–	0.72 %	0.38 %
MAC	0.03	0.31	2.24 %	4.73 %	6.38 %	4.66 %	6.38 %
HOM	0.01	0.22	2.07 %	4.34 %	–	3.59 %	4.34 %
BSH	0.12	0.29	1.12 %	5.16 %	–	5.16 %	5.16 %
SWO	0.04	0.22	1.60 %	3.55 %	2.49 %	2.60 %	2.49 %
WHB	-0.03	0.98	0.81 %	4.78 %	11.05 %	3.62 %	0.81 %
BET	0.28	0.68	0.33 %	5.56 %	3.41%	5.56 %	3.41 %
HKP	0.12	1	0.02 %	3.99 %	–	3.56 %	3.99 %
COD	0.1	0.27	0.53 %	2.91 %	2.82 %	2.05 %	2.82 %
ALB	0	0.44	1.20 %	2.48 %	4.19 %	1.97 %	4.19 %
MAZ	-0.26	1	0.02 %	8.21 %	–	0.64 %	0.02 %
PEL	-0.06	1	0.01 %	7.83 %	–	0.05 %	0.01 %
SQA	-0.01	1	0.05 %	2.64 %	–	1.34 %	1.01 %
GRO	-0.51	1	0.00 %	3.43 %	–	0.02 %	0.00 %
OCC	-0.04	0.36	0.64 %	1.39 %	–	0.78 %	0.64 %
FIN	-0.23	0.84	0.21 %	2.14 %	–	0.21 %	0.21 %
PAT	0.13	1	0.14 %	1.7 3%	–	1.35 %	1.73 %
BOG	0.19	0.58	0.14 %	2.02 %	–	1.05 %	2.02 %
OCT	-0.46	1	0.01 %	2.08 %	–	0.02 %	0.01 %
PRC	-0.18	1	0.01 %	3.19 %	–	0.01 %	0.01 %
RED	-0.12	1	0.22 %	1.96 %	0.52 %	0.48 %	0.22 %
LEZ	-0.02	0.27	0.50 %	1.30 %	1.65 %	0.63 %	1.65 %
NOX	-0.04	1	0.27 %	1.73 %	–	0.54 %	0.27 %
TUN	-0.29	1	0.09 %	2.79 %	–	0.11 %	0.09 %
SQP	0.06	1	0.03 %	1.48 %	–	1.11 %	0.03 %
ANF	0	0.11	0.61 %	0.90 %	0.96 %	0.75 %	0.96 %
GHL	-0.01	0.45	0.44 %	1.05 %	0.89 %	0.57 %	0.89 %
POA	-0.41	1	0.01 %	2.08 %	–	0.01 %	0.01 %
MNZ	-0.33	1	0.02 %	1.63 %	0.78 %	0.04 %	0.02 %
COE	-0.08	0.56	0.24 %	1.37 %	–	0.32 %	0.24 %
GAD	-0.08	1	0.03 %	3.23 %	–	0.17 %	3.23 %
HKX	-0.67	1	0.00 %	1.94 %	–	0.00 %	0.00 %
SKA	-0.09	0.7	0.30 %	1.00 %	0.53 %	0.30 %	0.30 %
SQI	0.01	1	0.18 %	1.22 %	–	0.22 %	0.76 %
GRM	0	1	0.00 %	0.90 %	–	0.28 %	0.90 %
					Overall Return ($\overline{R}_j$)	**0.051**	**0.051**
					Δ Return	–	(const.)
					Overall Risk ($CVaR_j$)	**0.38**	**0.23**
					∇ Risk	–	(−39.65 %)

Notes: Landings mean returns ($\overline{R}_{ij}$), risk ($CVaR_{ij}$), minimum constraint (w_{ij}^{min}), maximum constraint (w_{ij}^{max}), quota constraint (w_{ij}^{quota}), last observed weight (Last Obs. (w_{ijt})), and suggested efficient weight (w_{ij}*) for each of the fish species (i) and country (j = Spain). The Overall Return ($\overline{R}_j$) is the overall return of the fish portfolio, Δ Return is the return increase of the efficient portfolio over the last observed distribution, Overall Risk ($CVaR_j$) is the overall risk of the fish portfolio and ∇ Risk is the risk decrease of the efficient portfolio over the last observed distribution.

reduces risk by 39.65 %. Due to the redistribution of landings, the overall risk has been considerably reduced to CVaR= 0.23. These results indicate that the mean increase of landings in Spain would be 5.1 %, and in the worst case, landings would be reduced by 23 %.

3.1.9. United Kingdom

The number of fish species fulfilling the species inclusion criterion in the UK is 21 (N'_{UK}=21). The leading species, i.e. Atlantic mackerel (MAC), constitutes on average the 25 % of total landings in the UK, and the five outstanding species concentrate 56 %. Both, Atlantic mackerel (MAC) and Atlantic herring (HER), have negative mean returns and quite high risk. This is the main reason why our proposal suggests reducing their proportion to the minimum observed weight (respectively 21.59 % and 9.73 %). On the contrary, European plaice (PLE) has a positive mean return ($\overline{R}_{PLE,UK}$=0.04) and low risk ($CVaR_{PLE,UK}$=0.12). Hence, we suggest increasing its proportion up to 9.04 %, which is the maximum allowed weight by quota regime.

The last plot in Fig. 4 shows the FEF for United Kingdom. Although it is similar to the Belgian and Irish FEFs, it has some noticeable differences. The return of the minimum risk portfolio (MRP) is below the return of the portfolio for the last observed distribution (black square). Therefore, as third-best strategy, we suggest the constant return portfolio (CRP) (grey star) that keeps the return constant but reduces risk by 40.28 %. Due to the suggested redistribution of landings for the United Kingdom, the mean increase of landings would be 0.3 %, and in the worst case, landings would be reduced by 7 %.

3.2. Summary of the key efficiency gains

Table 3 summarises the key efficiency gains for each of the nine EU member-states. According to our individualized proposals, some countries (i.e. Germany, Denmark, Spain, France and United Kingdom) would keep the observed return constant; however, they would reduce their risk considerably. Other countries (i.e. Belgium, Ireland, the Netherlands and Portugal) would increase their return and, at the same

Table 12
Landings return, risk and specific weights for the United Kingdom.

Species	$\overline{R}_{ij}$	$CVaR_{ij}$	w_{ij}^{min}	w_{ij}^{max}	w_{ij}^{quota}	Last Obs. (w_{ijt})	w_{ij}*
MAC	-0.01	0.4	21.59 %	34.48 %	62.4 %	27.09 %	21.59 %
HER	-0.04	0.33	9.73 %	15.98 %	24.13 %	11.84 %	9.73 %
HAD	0	0.12	6.59 %	9.06 %	11.46 %	7.65 %	6.59 %
SCE	0.03	0.11	4.49 %	7.98 %	–	6.50 %	4.49 %
CRE	0.02	0.13	4.97 %	6.96 %	–	6.83 %	4.97 %
NEP	-0.04	0.19	4.10 %	6.89 %	12.49 %	4.65 %	4.10 %
WHB	-0.09	1	0.88 %	11.63 %	14.92 %	3.2 8%	2.96 %
WHE	0	0.53	3.05 %	5.36 %	–	3.35 %	3.05 %
POK	0.01	0.13	2.96 %	4.23 %	3.89 %	3.38 %	3.89 %
COD	0.04	0.27	2.15 %	4.47 %	7.00 %	4.47 %	7.00 %
HKE	0.15	0.07	0.98 %	4.77 %	2.46 %	4.77 %	2.46 %
QSC	-0.01	0.75	1.12%	5.90 %	–	1.23 %	4.89 %
WHG	-0.03	0.15	2.05%	3.07 %	3.29 %	2.45 %	2.05 %
ANF	0.03	0.54	1.78%	3.36 %	3.93%	3.36 %	3.93 %
COC	-0.08	1	0.16%	3.40 %	–	1.27 %	3.19 %
JAX	-0.15	1	0.39%	3.53 %	5.13 %	0.41 %	0.39 %
LIN	0.07	0.05	0.77%	1.67 %	1.54 %	1.67 %	1.26 %
SPR	0.02	0.33	0.71%	1.62 %	2.7 7%	0.98 %	0.71 %
CTL	0.05	0.48	0.58%	1.80 %	–	1.80 %	1.80 %
PIL	0.1	0.15	0.55%	1.89 %	–	1.79%	1.89 %
PLE	0.04	0.12	0.75%	1.21 %	9.04 %	1.21 %	9.04 %
					Overall Return ($\overline{R}_j$)	**0.003**	**0.003**
					Δ Return	–	(const.)
					Overall Risk ($CVaR_j$)	**0.11**	**0.07**
					∇ Risk	–	(−40.28 %)

Notes: Landings mean returns ($\overline{R}_{ij}$), risk ($CVaR_{ij}$), minimum constraint (w_{ij}^{min}), maximum constraint (w_{ij}^{max}), quota constraint (w_{ij}^{quota}), last observed weight (Last Obs. (w_{ijt})), and suggested efficient weight (w_{ij}*) for each of the fish species (i) and country (j = United Kingdom). The Overall Return ($\overline{R}_j$) is the overall return of the fish portfolio, Δ Return is the return increase of the efficient portfolio over the last observed distribution, Overall Risk ($CVaR_j$) is the overall risk of the fish portfolio and ∇ Risk is the risk decrease of the efficient portfolio over the last observed distribution.

time, reduce their risk. The country with the highest increase on return would be the Netherlands (+239.51 %) and the ones with the highest decrease on risk would be France (−97.98 %) and Ireland (−90.39 %).

4. Discussion

Our study has three major limitations, which should be addressed in the future. First, we are ignoring the market as we are using the weight but not value. This could be done in a further step, not covered in the paper. It might be potentially addressed by estimating value-based FEFs which internalizes the market, and would likely cause changes in the estimations. For sure, some estimations would change. For example, Atlantic herring is the leading fish species in terms of quantity (16 % of total landings in the EU in 2018), but, it only constitutes 3 % of the total value. However, one of the main advantages of using weight instead of value is that TACs on species are based on quantity. We could also estimate the value of TACs, but, adjusting prices for each fish species in each country would generate additional concerns.

Second, the aggregation level is a key question in the analysis. Obviously, a community level approach would be more connected to reality. We need a minimum time series of landings by fish species, within the same country/region/fleet/community to run the optimization problem. Unfortunately, the data availability to focus on a community level approach is still limited. We are conscious that, unfortunately, we are ignoring the distributional consequences of redistributing landings within fishing communities operating in the fishing countries. This means that whenever we are changing one species by another, we are ignoring communities that are fishing exactly the same fish species and the fact that fishers going for one fish species may not be ready to go for another. Thus, it may be necessary to work with community profiles when addressing fisheries governance issues.

Third, ecological perspective is a major limitation of our study. Fish at high trophic levels often have lower biomass, but sell at higher prices than those at low trophic levels. In this context, our optimization approach would implicitly give more weight on low trophic fish when estimating efficient fish portfolios. The estimated efficient catch composition might not result in effective financial incentives for fishermen since our application lack an ecological base. A possible solution would be to use different inclusion criteria. That is to say, we could separate groups of fish species by trophic level and/or prices, even if this possibility is beyond the scope of this article. This way, we could find the efficient distribution of fish species at different trophic levels and/or price levels (e.g. small and medium pelagic, which are captured by either encircling nets (to catch anchovy, mackerel and horse mackerel), troll line or pole (to catch white tuna)).

Notice that our approach is flexible and could be adapted to any other particular ecosystem. In fact, additional constraints may be added to the model in order to analyse how different strategies or limitations would affect the overall efficiency of the fish portfolios. This way, different ecological, economic and social objectives could be incorporated into the model. Comparing different scenarios could be helpful to quantify changes on risk and return levels, and observe how different decisions would affect the reallocation of our recommended weights. There are also potential scenarios to be explored by the inclusion of a sustainability parameter (γ) in the risk minimization problem (Sanchirico et al., 2008; Jin et al., 2016; Carmona et al., 2020). It would be useful to simulate possible policies and observe how these decisions would affect the reallocation of landings. Policy makers could use this modelling as a complementary tool to improve their decision-making and stock assessments. For instance, let's consider 3 different values for γ, { $\gamma = 1$, $\gamma = 0.85$, $\gamma = 1.15$} in order to simulate three potential policies when setting the maximum catch limits. If $\gamma = 1$, we ensure that only weights below the w_{ij}^{quota} are allowed. While $\gamma = 1.15$ and $\gamma = 0.85$ imply that the w_{ij}^{quota} levels could be respectively increased by 15 % and reduced by 15 %. Through the comparison of these three potential scenarios we could observe how policy makers' decisions could affect the reallocation of landings, and therefore, the resulting changes in both returns and risks.

There are potential gains from transferring quota rights between countries that would increase return, reduce risk, and help their fish

Table 13
Fish species codes, scientific and English names.

CODE	Scientific name (English name)	CODE	Scientific name (English name)
ALB	Thunnus alalunga (Albacore)	MON	Lophius piscatorius (Angler (=Monk))
ANE	Engraulis encrasicolus (European anchovy)	MUR	Mullus surmuletus (Surmullet)
ANF	Lophiidae (Anglerfishes)	MUS	Mytilus edulis (Blue mussel)
BET	Thunnus obesus (Bigeye tuna)	NEP	Nephrops norvegicus (Norway lobster)
BIB	Trisopterus luscus (Pouting (=Bib))	NOP	Trisopterus esmarkii (Norway pout)
BLL	Scophthalmus rhombus (Brill)	NOX	Nototheniidae (Antarctic rockcods, noties)
BOC	Capros aper (Boarfish)	OCC	Octopus vulgaris (Common octopus)
BOG	Boops boops (Bogue)	OCT	Octopodidae (Octopuses, etc.)
BOR	Caproidae (Boarfishes)	PAT	Patagonotothen ramsayi (Longtail Southern cod)
BRB	Spondyliosoma cantharus (Black seabream)	PEL	Osteichthyes (Pelagic fishes)
BSF	Aphanopus carbo (Black scabbardfish)	PIL	Sardina pilchardus (European pilchard(=Sardine))
BSH	Prionace glauca (Blue shark)	PLE	Pleuronectes platessa (European plaice)
BSS	Dicentrarchus labrax (European seabass)	POA	Brama brama (Atlantic pomfret)
CAP	Mallotus villosus (Capelin)	POK	Pollachius virens (Saithe (=Pollock))
CNZ	Crangon spp (Crangon shrimps)	POL	Pollachius pollachius (Pollack)
COC	Cerastoderma edule (Common edible cockle)	PRC	Percoidei (Percoids)
COD	Gadus morhua (Atlantic cod)	QSC	Aequipecten opercularis (Queen scallop)
COE	Conger conger (European conger)	REB	Sebastes mentella (Beaked redfish)
CRE	Cancer pagurus (Edible crab)	RED	Sebastes spp (Atlantic redfishes)
CSH	Crangon crangon (Common shrimp)	RJC	Raja clavata (Thornback ray)
CTC	Sepia officinalis (Common cuttlefish)	RJH	Raja brachyura (Blonde ray)
CTL	Sepiidae, Sepiolidae (Cuttlefish, bobtail squids)	RJN	Raja naevus (Cuckoo ray)
DAB	Limanda limanda (Common dab)	SAA	Sardinella aurita (Round sardinella)
DGZ	Squalus spp (Dogfishes)	SAN	Ammodytes spp (Sandeels (=Sandlances))
FIN	Osteichthyes (Finfishes)	SBA	Pagellus acarne (Axillary seabream)
FLE	Platichthys flesus (European flounder)	SBR	Pagellus bogaraveo (Blackspot(=red) seabream)
GAD	Gadiformes (Gadiformes)	SCE	Pecten maximus (Great Atlantic scallop)
GHL	Reinhardtius hippoglossoides (Greenland halibut)	SCL	Scyliorhinus spp (Catsharks, nursehounds)
GKL	Glycymeris glycymeris (Common European bittersweet)	SCR	Maja squinado (Spinous spider crab)
GRO	Osteichthyes (Groundfishes)	SDV	Mustelus spp (Smooth-hounds)
GUR	Aspitrigla cuculus (Red gurnard)	SKA	Raja spp (Raja rays)
GUU	Chelidonichthys lucerna (Tub gurnard)	SKJ	Katsuwonus pelamis (Skipjack tuna)
HAD	Melanogrammus aeglefinus (Haddock)	SOL	Solea solea (Common sole)
HER	Clupea harengus (Atlantic herring)	SPR	Sprattus sprattus (European sprat)
HKE	Merluccius merluccius (European hake)	SQA	Illex argentinus (Argentine shortfin squid)
HKP	Merluccius hubbsi (Argentine hake)	SQC	Loligo spp (Common squids)
HKX	Merluccius spp (Hakes)	SQI	Illex illecebrosus (Northern shortfin squid)
HOM	Trachurus trachurus (Atlantic horse mackerel)	SQP	Loligo gahi (Patagonian squid)
JAA	Trachurus picturatus (Blue jack mackerel)	SQZ	Loliginidae (Inshore squids)
JAX	Trachurus spp (Jack and horse mackerels)	SWO	Xiphias gladius (Swordfish)
LAH	Laminaria hyperborea (North European kelp)	SWX	Algae (Seaweeds)
LEM	Microstomus kitt (Lemon sole)	SYC	Scyliorhinus canicula (Small-spotted catshark)
LEZ	Lepidorhombus spp (Megrims)	TUN	Thunnini (Tunas)
LIN	Molva molva (Ling)	TUR	Scophthalmus maximus (Turbot)
LQD	Laminaria digitata (Tangle)	ULO	Spisula solida (Solid surf clam)
MAC	Scomber scombrus (Atlantic mackerel)	VMA	Scomber colias (Atlantic chub mackerel)
MAZ	Scomber spp (Scomber mackerels)	WHB	Micromesistius poutassou (Blue whiting(=Poutassou))
MEG	Lepidorhombus whiffiagonis (Megrim)	WHE	Buccinum undatum (Whelk)
MNZ	Lophius spp (Monkfishes)	WHG	Merlangius merlangus (Whiting)
MOL	Mollusca (Marine molluscs)	YFT	Thunnus albacares (Yellowfin tuna)

Notes: 3-alpha identifier code, scientific name and English name in brakets.

landings be more efficient. Member-states are responsible for ensuring that fish species are not overfished above quota limitations. Whenever a country reaches the allowed quota, the European Commission allows them to manage and transfer quota limits during the year (EU, 2017). Since the mid-eighties, many authors have suggested that improving transferability of quota rights could be a feasible solution to reduce overcapacity and generate resource rents in the fishery (Arnason, 1990, 1996; Weninger, 1998; Asche et al., 2008; Branch, 2009). Hence, the fact that countries would not only transfer catching rights, but also return and risk, deserves special attention. Therefore, these potential quota exchanges could also be considered when portfolio selection model is optimized. Furthermore, our proposal could imply different strategies depending on the country.

Some fish species are catalogued as low return and high risk for some countries, and inversely as high return and low risk for others, depending on their temporal performance. For instance, according to our efficient portfolio reweighting proposals, Spain and Portugal should increase their landings of albacore, while France should reduce it. Therefore, there would exist potential quota transfer interests among these countries, which would benefit the three of them in financial terms (i.e., a win-win-win solution). Something similar happens with bigeye tuna. While Spain is suggested to reduce bigeye tuna, the advice for Portugal is increase bigeye tuna weight. The recommendation for France and Belgium is to reduce their quantity of Atlantic cod landed. Contrarily, Portugal, United Kingdom, Denmark and Spain, should increase its weight. In addition, blue whiting is considered a risky species for all the countries except for France. Therefore, our suggestion is to increase the proportion of blue whiting for France, and to reduce it for the rest of the countries. Thus, countries should consider the possibility of transferring blue whiting catching rights to France, in order to make their fish portfolio even more efficient.

5. Concluding remarks

In the framework of the seminal work of Sanchirico et al. (2008), in this paper we provide an innovative tool for EU fishing policy makers to potentially redirect multispecies fisheries management using modern portfolio theory (MPT). Efficient portfolios allows one to observe how fishing countries have performed in the past, and how they could perform better in the future by reallocating their fish landings, increasing (or at least maintaining) their observed return levels, and reducing their risk. Taking advantage of the discussion of the pure financial literature supporting the use of the downside risk indicators (Matthies et al., 2019), we have contributed to the literature of financial fisheries economics, developing a feasible approach to manage downside uncertainty in fisheries outcomes. To the best of our knowledge, this is the first paper using CVaR in fisheries.

Based on a constrained risk minimization problem, we have estimated country specific efficient financial frontiers. Then we have recommended an efficient reallocation of landings for Belgium, Denmark, France, Germany, Ireland, the Netherlands, Portugal, Spain and United Kingdom. Our efficient portfolio proposals are based on historical landings data, which incorporate changing ecological, economic and regulatory factors. Therefore, our approach is able to detect excessive landings of some species and excessive risk taking (Jin et al., 2016).

Our major finding is that countries could benefit by adopting a mean-CVaR optimization approach. Countries could considerably reduce risk and also increase, or at least maintain previous return levels by reallocating their landings. This way we are able to propose a redistribution of fish species weights and suggest how individual countries should increase or reduce landings of some fish species, under sustainable limits, in order to perform better. Following our proposals, Belgium could achieve a higher return (+181 %) at a lower risk (−34.02 %), compared to the portfolio for the last observed distribution. Ireland could increase return by +52.10 % and reduce risk by −90.39 %. The Netherlands could increase return by +240 % and reduce risk by −61 %. In the case of Portugal, it could be possible to achieve a higher return (+11.92 %) at a lower risk (−57.13 %). As a second-best strategy, we suggest maintaining the return constant, but considerably reducing risk for Germany (−8.42 %), Denmark (−33.41 %), Spain (−39.65 %), France (−97.98 %) and United Kingdom (−40.28 %). Summarising, all the countries could benefit by adopting a mean-CVaR optimization approach as a tool to manage fisheries efficiently and account for species interactions.

CRediT authorship contribution statement

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Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Itsaso Lopetegui reports financial support was provided by Dpto. de Educación, Política Lingüística y Cultura del Gobierno Vasco through Beca Predoctoral de Formación de Personal Investigador no Doctor and research grant EGONLABUR from the same department. Ikerne del Valle reports financial support was provided by panish Ministry of Economics and Competitiveness. Project Ref RTI2018- 099225-B-I00.

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Appendix A

Tables 4–12 capture the observed and suggested portfolios for each individual country and their respective last observed weights (w_{ijt}) and the suggested efficient weights (w_{ij}*). Following our proposal, countries could achieve an efficient distribution of fish landings that increases or, at the worst, maintains constant the observed return, and significantly reduces risk. Notice that we are using the 3-alpha identifier in Tables 4–12. However, the complete list of fish species, including codes, scientific names and English names is shown in Table 13.

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