Comparing economic and biological management objectives in the commercial Baltic salmon fisheries

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ABSTRACT

This paper compares two fisheries management objectives recognized in the literature and applied in practice: maximum sustainable yield (MSY) and maximum economic yield (MEY). The European Union Common Fisheries Policy (CFP) sets the minimum target of fish populations at the MSY level, defined as the stock level that maximizes the fish catch. Although MSY is useful in nudging over-harvested stocks back to biologically sustainable levels, the CFP requires the harvested stocks to be maintained above levels that can produce MSY without addressing the exact definition of "above MSY". One possibility for maintaining fish stocks above MSY is to apply the maximum economic yield (MEY) that maximizes the discounted net present value of the fishery. Comparison of the economic and ecological outcomes of the two objectives in the Northern Baltic salmon fishery is conducted by applying a dynamic optimization model coupled with age-structured salmon stock dynamics. The results are further tested for the changes in stock-recruitment parameters, and related to the precautionary management target of reaching 75% smolt production capacity. A sensitivity analysis for the economic parameter values is conducted. The results show that as a target, MEY performs better than MSY in both conserving the stocks and providing economic viability for the fishers. Targeting MEY while keeping MSY at hand as a minimum biological objective was found to be a pragmatic objective that is in line with the goals of the CFP and the EU Blue Growth Strategy.

1. Introduction

Fisheries management aims to ensure the long-term sustainable use of fish stocks among other desirable outcomes. A selection of reference points are used as tools to relate the ecological realities of fish stock dynamics with the management objectives. With varying success and failure, maximum sustainable yield (MSY) has been widely applied as a management objective that is said to define an operational and quantifiable goal (e.g., [18,38,45]). The European Union Common Fisheries Policy (CFP) [11] is one example from the adherents of MSY – the overall management target of the CFP is to maintain harvested fish stocks above MSY levels. MSY defines the maximum level of harvest that can be taken without reducing the stock size in the long run. Stated more fully, harvesting at the level of MSY results in the maximum growth rate of the population. In the CFP, MSY answers the need of defining a minimum sustainable level of fish stocks from a biological point of view. This target is important since the fishing mortality

exceeds the MSY level in 50% of fish stocks[1] in the EU [50].

There is, however, another set of requirements for a sound management target aside from the biological definition of sustainability. According to these general fisheries management requirements – also stated in the EU CFP [11] – economic, social and employment benefits as well as the availability of food must be consistently taken into account [35]. The lack of correspondence between the multiple, and at times even conflicting, objectives of the CFP is striking, as is the mere definition of a limit reference point at MSY, yet not uncommon when viewed from a global perspective [9,16]. No precise formulation of "above MSY" stock levels is provided, nor is a further quantifiable goal given to meet the economic, social and employment benefits in the CFP. It is clear that if fisheries management is to meet sustainability by combining biological, economic and social dimensions, it is not sufficient that its goals be only implicitly defined [6].

To this end, the use of a management objective called maximum economic yield (MEY) in the case of Northern Baltic salmon fishing is

explored, and compared with targeting MSY. Instead of maximizing the harvest, MEY maximizes the sum of discounted net present value of the fishery over time to capture the effects of catch price, fishing costs and discounting [19,30]. To test the pragmatic MEY objective that is in line with both the CFP and the EU Blue Growth Strategy [10], as well as the traditional MSY objective, a sensitivity analysis is conducted. In addition, the biological uncertainty over the stock-recruitment parameters is considered by reproducing the modelling results with the stock-recruitment parameters from the years 2010–2014. The results of both MEY and MSY management are compared against the precautionary target set by the International Council for the Exploration of the Sea (ICES) of reaching 75% of the Potential for Smolt Production Capacity (PSPC) [20].

2. Fisheries management targets in theory and practice

Alongside the biological realities of fish stocks, fishing is essentially driven by the economic maximization of fishing activity, and the potential economic benefits from an efficiently managed fishery are well established [12,13,51]. The availability of fish stocks changes over time, which makes the continuum of time important in fisheries management: Scott [51] states that the prospects for efficiency in fisheries management strategies increase when moving from short-term to long-term management. The trade-off between fishing now or later, i.e., choosing to harvest the fish to gain the profits immediately versus contributing to future fish resources by conserving the fish while having to wait for the profits, is highlighted in the seminal work on dynamic definition of MEY [2,3].

Whether MEY can perform better than MSY is under debate. The biological, economic, and social goals are essentially conflicting: for example, MSY provides maximum biological production, yet failing to maximize employment, ecosystem preservation and economic profitability [16,48]. Hilborn [16] also points to the similarities of environmental protection and economic maximization in that proponents of these objectives would prefer high fish biomasses alongside stable catches and low fishing effort. Grafton et al. [14] argue that a fish stock at MEY is bigger than a stock at MSY as long as the prices, costs, and discount rates are reasonable, which is opposed by Clark et al. [4], who suggest that the possibility of stock extinction under MEY management cannot be ignored. In response to the critique, Grafton et al. [55] show that if the current biomass level is lower than a dynamic MEY solution, no trade-off between stock conservation and profitability exists. The global performance of MEY was tested within a surplus-production model setup where data from 4713 fisheries was analysed to find that a management regime relying on MEY simultaneously maximizes the global annual profits and biomass [5]. Large differences between MSY and MEY objectives emerge when the objectives are compared using dynamic age-structured modelling and endogenous harvesting selectivity [53].

As shown above, the simulations of MEY management are plentiful in the literature; however, MEY has been implemented only recently as a practical policy. In Australia, for example, the MEY based management of the northern prawn fishery (NPF) was implemented in 2008, and has recently earned a sustainability certificate from Marine Stewardship Council [44]. Initially, the underlying bioeconomic model built to support the NPF entailed a delay-difference model [7,30], which was updated to consider the size-structured stock dynamics, an integrated profit function and forward projections of size-related prawn price and fuel costs [46]. Building on the experiences from the NPF management, Dichmont et al. [8] present challenges that occur in implementing MEY in practice, especially in specifying the bioeconomic estimation of MEY. Norman-López and Pascoe [42] found that the MEY based management in the NPF resulted in overall losses in the short term, but net economic benefit was created in the long term. Despite the challenges in specifying the bioeconomic estimation of an MEY target, the Australian example indicates that the challenges can be overcome

[19]. In 2007, the Parties to the Nauru Agreement implemented a transferable effort scheme in the Western and Central Pacific Ocean tuna fisheries aiming for maximizing economic returns in the long run [15].

The Baltic salmon stocks are utilized by sequential fisheries, including international commercial offshore long lining, commercial coastal trap net fishing and recreational angling in rivers. The sequential nature of the fishery is explained by the anadromous life cycle – salmon are born in a specific natal river, migrate to the sea, and return to the natal river for spawning – in addition to the spatial extent of salmon feeding and spawning migrations. During the spawning migration, salmon are targeted by trap nets along the migration route on the coast, and then by recreational anglers at the river. The salmon stock of the River Tornionjoki is by far the largest salmon stock in the Baltic Sea region, accounting for about half of all wild salmon in the region [25]. Coastal trap nets are the most important item of gear in the Baltic commercial salmon fishery; in 2016, trap net fishing caught 57.5% of the total nominal catches in the Baltic Sea region [26]. Tornionjoki river stock contributes to 34% of the total salmon abundance in the Gulf of Bothnia and is predominantly harvested on the Finnish coast of the Gulf [25]. The ICES uses the Potential Smolt Production Capacity (PSPC) as the basis for estimating the reference points, and suggests to reach at least 75% of the PSPC in order to recover the salmon populations to the MSY level [20].

Thus, given the important role of the Tornionjoki in reproduction and catches especially to the Finnish salmon fishing industry, the focus of this paper is on the Tornionjoki river stock. Furthermore, Finnish economic data for the economic parameters is used. The harvesting quota for salmon is set for professional fishing only, and since the recreational fishing is not explicitly considered in quota decisions, this paper considers only the biological effect of recreational fishing on the amount of eggs produced by spawners. This paper analyses the relative performance of MSY and MEY objectives in the commercial trap net fishery targeting salmon of the River Tornionjoki in the Northern Baltic Sea to deepen the understanding of how to integrate economics into fisheries management decisions. Bioeconomic modelling coupled with dynamic optimization is used in order to compare the economic and ecological effects of targeting MEY, which maximizes the discounted benefits from the fishery or MSY, which maximizes the harvest. Both objective functions are built upon an age-structured salmon stock model. Additionally, the biological uncertainty of changes in stock-recruitment parameters was analysed, and an economic sensitivity analysis was carried out. The outcomes of MSY and MEY objectives are analysed with respect to the generic ICES scientific advice (2008) of targeting 75% of PSPC.

3. Bioeconomic model of the Northern Baltic salmon fishery

3.1. Tornionjoki salmon stock dynamics and harvesting

To foster the inclusion of time-delay effects in the modelling of structured population (e.g. Tahvonen [52]), an age-structured modelling approach is utilized for describing the salmon stock dynamics in this paper. The age-structured salmon population dynamics are based on the model first described in Holma et al. [17] and Appendix A describes the model and its parameters in detail. The baseline biological parameters values are listed in Tables A.1 and A.2. The salmon stock develops according to the following function, which specifies the number of salmon aged $i=(1,...,10)$ at Baltic Main Basin before coastal fishing at time $t+1$ ($s_{ob,i,t+1}$) as a function of the life history matrix $A_{ob,t}$ and the number of salmon aged i at time t under the chosen management objective $ob=$(MEY or MSY): $s_{ob,i,t+1} = A_{ob,t}s_{ob,i,t}$.

The number of homing salmon ($sp_{ob,i,t}$) of age i at time t is therefore given by $sp_{ob,i,t} = s_{ob,i,t}e^{-mS}y_i$, where mS is the instantaneous natural mortality for homing salmon and vector y_i is the share of salmon of age i heading to the spawning river. The coastal catch of Tornionjoki river

Table 1
Economic parameter values.

Symbol	Definition	Value	Source (Unit)
θ	Tornionjoki salmon in total catch	0.345	ICES (2015)
c	Unit cost of effort for a seal-safe trap net Proportion of	47.945θ	Kulmala et al. [56][a] (€ / gearday)
p_i	Average age-specific catch price	[0 0 0 0 9.127 30.54 56.13 54.92 66.25]	Luke (2015) (€ / fish)

[a] The unit cost in coastal trap net fishing is based on Kulmala et al. [56], as updated in Salenius [57], and converted to 2015 euros [58].

stock is almost entirely harvested by the Finnish coastal trap net fleet [27]. The amount of homing salmon is used as an input in the harvest function of the coastal trap net fleet:

$$H_{ob,i,t} = \left(1 - e^{-q_i E_{ob,t}}\right) s p_{ob,i,t} \tag{1}$$

Thus, the annual profits ($\pi_{ob,t}$) of the fishery under a chosen management objective, summed over the salmon age groups i, are defined by the total revenue minus the total costs from harvesting:

$$\pi_{ob,t} = \sum_{i=1}^{10} p_i H_{ob,i,t} - c E_{ob,t} \tag{2}$$

where fishers face the age-specific salmon wholesale prices for gutted salmon, p_i, and linear costs per unit of effort, c, multiplied by the choice variable, fishing effort $E_{ob,t}$. The economic parameter values are presented in Table 1. The fishing effort is expressed in geardays defined as units of gear multiplied by the number of fishing days. The cost per unit of effort is scaled with the parameter θ to match the costs with the proportion of the catch originating from Tornionjoki river in the total salmon catch.

3.2. Dynamic optimization model

To quantify the economic and ecological effects of targeting either MEY, which maximizes the discounted benefits from the fishery, or MSY, which maximizes the harvest, a dynamic optimization model is used. The projections over a 100 year time period are carried out using a KNITRO[2] nonlinear optimization toolbox "knitromatlab" in MATLAB 8.3.[3]

3.2.1. Maximum economic yield (MEY)

The MEY management objective *(ob = MEY)* takes into account the economic characteristics of the coastal trap net fishery, including salmon catch prices, fishing costs and discounted value of future benefits, in calculating the revenues from harvesting. To discount future benefits, an economic discount rate ($r = 0.03$) is used. Following the approach of Kompas et al. [30] the MEY management target maximizes the sum of discounted net present value of the fishery over time by choosing the optimal level of fishing effort:

$$NPV_{MEY} = \max_{E_{MEY,t}} \sum_{t=1}^{100} \frac{[\pi_{MEY,t}]}{(1+r)^{t-1}} \tag{3}$$

subject to an initial guess that geardays, an initial condition of $s_{i,1}$, $s_{MEY,i,t+1} = s_{MEY,i,t} A_{MEY,t}$ and the constraint that $H_{MEY,i,t} = (1 - e^{-q_i E_{MEY,t}}) y_i s_{MEY,i,t}$.

3.2.2. Maximum sustainable yield (MSY)

In calculating MSY, the objective is to find the optimal level of annual effort that maximizes the harvest over time *(ob = MSY)*. The optimization problem under MSY management is defined as follows:

$$MSY = \max_{E_{MSY,t}} \sum_{t=1}^{100} [H_{MSY,i,t}] \tag{4}$$

subject to an initial guess of $E_{MSY,1} = 5000$, an initial condition of $s_{i,1}$, $s_{MSY,i,t+1} = s_{MSY,i,t} A_t$ and the constraint that $H_{MSYi,t} = (1 - e^{-q_i E_{MSY,t}}) y_i s_{MSY,i,t}$.

4. Results

4.1. Comparing the management objectives

Solving the dynamic optimization models presented in Eqs. (3) and (4) to find the effort level that either maximizes the harvest (ob = MSY) or the net present value (ob = MEY) yields the results depicted in Fig. 1 and in Table 2. The models are populated with stock-recruitment parameters from the assessment year 2013. The generic advice from the ICES of targeting 75% of the PSPC in the Baltic Sea [20] is used to determine how the modelling results relate to the long term precautionary objective. The river specific smolt production targets used in the ICES advice vary between 60% and 80% of the PSPC.

The largest steady state fishing effort (Fig. 1a) was realized under MSY management, and it took approximately 30 years to reach the long run equilibrium. The optimal effort level under the MEY management target required a moratorium on the salmon fishery for first two years, because the initial population was low, and the moratorium allowed the stock to recover. As the model assumes perfect malleability, the adaption costs of the fishery incurred by the moratorium are not explicitly treated. Comparing the average actual effort level from 2013 to 2016 to the optimization results (Fig. 1a) reveals that the actual effort levels have been close to the optimized MSY effort level in 2013 and 2014.

The summed discounted net present value of maximizing the harvest under MSY is 4.06 M€, whereas maximizing the value of the fishery under MEY yields a net present value that is three times higher (Table 2). Annual undiscounted fishery profits were calculated using Eq. (2) and were positive over time for both the MSY and MEY objectives (Fig. 1b). During the first seven years of optimization, the profits were similar under both management objectives, and MSY performed slightly better during this initial period. However, in the long term, the steady state profits under MEY were more than two times the profits under MSY. The economic efficiency of effort defined as the ratio of profits per effort under MEY was relatively higher than under MSY, since the profits were considerably lower under MSY than under MEY while there was a smaller disparity in harvest levels (Fig. 1c). Under MSY, the cost of unit of harvest is much higher than under MEY. Assuming that Finland targets the MSY level instead of MEY, the fishing sector will lose 263,000 € in annual profits in the long term.

The number of smolts, i.e., the number of salmon that begin the migration from the natal river to the Baltic Sea, represents the status of the salmon stock and is depicted in Fig. 1d. Under MSY, the smolt production over time was 23.5% smaller than the smolt production under the economic reference point. Using the biological data from year 2013, neither MSY nor MEY smolt level attained the PSPC target level. As the fishing effort in the initial periods is high under MSY management, the transition to the steady state smolt production is more pronounced during the first decade when compared to MEY management, which is essentially limited by the monetary cost placed on effort that
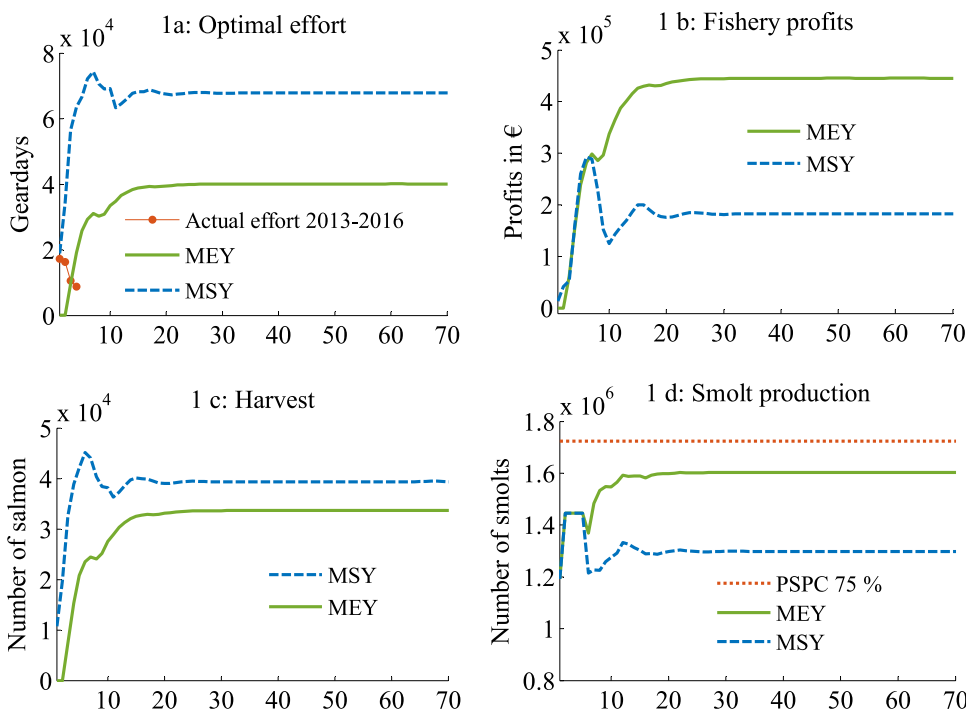
[2] Ziena.
[3] The MathWorks Inc.

Fig. 1. Optimal time paths for (a) fishing effort in geardays, (b) fishery profits in €, (c) harvest in number of salmon and (d) number of salmon smolts under MEY and MSY management with stock-recruitment parameters from assessment year 2013. The 75% of PSPC target is a generic MSY based objective proposed by the ICES [20]. Actual efforts from 2013 to 2016 refer to the commercial salmon trap net fisheries efforts from assessment unit 1 (AU1) [27]. Horizontal axis refers to time in years from 2013 onward.

acts as a buffer for changes in the number of smolts.

4.2. Effect of changes in salmon stock-recruitment parameters

There is considerable uncertainty in the year-specific estimates of salmon stock-recruitment parameters, which is reflected by the changes in the annual updates of the parameter estimates (Table 3). The bioeconomic optimization results given the stock-recruitment parameters estimated by the ICES in assessment years 2010–2014 (Table 3) were compared by repeating the optimization for the MSY and MEY objectives with the stock-recruitment parameters of the assessment years 2010–2014. Here, the steady state results of the optimization are presented.

With the assumed prices, costs and discount rate, choosing MEY management brought about higher profits and fish stocks in all years from 2010 to 2014. Fishery profits were consistently higher under MEY than under MSY management. With the stock-recruitment parameters from assessment year 2010, fishers face negative profits under MSY management in the long run, whereas under MEY management, the same data give 202 M€ in profit at the steady state. The fishing effort is consistently lower under MEY than MSY; the highest steady state level of effort is realized with data from the year 2012 that represents a high productivity of the stock (MSY 81,124 geardays, MEY 48,244 geardays), while the lowest effort is realized with data from the year 2010.

As shown in Fig. 2, from an economic point of view, the precautionary 75% of the PSPC target is feasible only with the biological parameters from assessment years 2011 and 2014. With parameters from assessment years 2010, 2012 and 2013, meeting the 75% of PSPC target would entail costs to society, as the fishing effort would be below the economic optimum level.

4.3. Variation of economic factors

Fish catch prices and fishing costs are central in MEY management. On the one hand, they make the fishery profitable and sustainable when the economic parameters are within reasonable limits. On the other hand, if the economic parameters become unreasonable in that prices are extremely high and costs low, the profits of the fishery may override its sustainability. To this end, the baseline scenario described in

Sections 3.2.1 and 3.2.2 is used with stock-recruitment parameters from year 2013 for the economic sensitivity analysis.

Due to the market integration of wild caught and farmed salmon in Finland, the price of imported farmed salmon determines the price of wild caught salmon [49]. Until recently, the price of wild salmon has decreased substantially as a result of increased competition with the readily available and cheap Norwegian farmed salmon. However, the global production of farmed salmon may decrease because of a continuing environmental and sanitary crisis in the Chilean salmon farming industry [34,36] and the slackening production growth of the Norwegian farmed salmon industry [1]. Since the demand for salmon is not decreasing, this may result in higher salmon prices. Thus, the MEY scenario is tested with respect to price changes. In addition, the effects of changes in the unit cost of effort and in the discount rate were analysed.

Changes in the economic factors affect the prospects of achieving the smolt production target as shown in Table 4. With a 30% decrease in prices the 75% of PSPC target is reached in the long-term. Increase in catch prices has to be very high to make the fishing effort high enough to reach the effort level in MEY that corresponds to the effort in MSY; a 3.6-fold increase in catch prices (the baseline wholesale price averaged over ages is 5.01 €/kg and the increase corresponds to 17.9 €/kg) made the steady state fishing effort under MEY higher than under MSY, which also resulted in a smolt production level smaller than it was under MSY. Discount rates had only minor effects on the salmon stock, whereas the summed net present value was affected. The role of the discount rate is generally considered small in fisheries management since it is usually dominated by the sensitivity of fishing costs to changes in the stock level [19].

5. Discussion and conclusions

In this paper, the performance of MEY as a management target that explicitly defines the level "above MSY" according to the CFP was analysed. Thus, the economic and ecological effects of targeting the maximized harvest (MSY) versus the maximized discounted net present value of the fishery (MEY) were compared by applying bioeconomic modelling and dynamic optimization based on age-structured salmon stock dynamics. The baseline modelling results show that choosing to

Table 2

Baseline modelling results and current mean coastal trap net harvest of Tornionjoki salmon in number of fish from ICES sub-divisions 29–31 over years 2010–2014.

	Sum of discounted net present value over time (M€)	Annual undiscounted profits at steady state (thousand €)	Annual commercial harvest in number of fish at steady state	Optimal annual steady state effort in gear days	Number of smolts at steady state (in millions) per year	Current mean commercial coastal harvest in number of Tornionjoki river stock fish over years 2010–2014[a]
Status quo						27,265
MSY	4.06	182.7	39,360	67,840	1.298	
MEY	12.01	445.3	33,660	40,059	1.603	

[a] Mean coastal harvest estimate is based on the results of the stock-assessment model by ICES [25] and includes a minor share of salmon harvest caught with gill nets.

Table 3

Stock-recruitment parameters for assessment years 2010–2014.

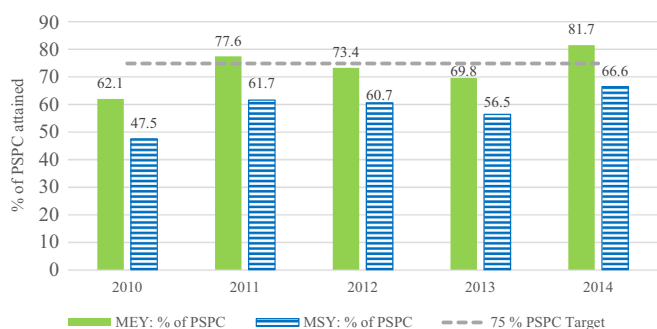| Year of assessment	Source	Alpha	Beta	PSPC median	PSPC 75%
2010	ICES [21]	77.16	0.000384	2,090,000	1,567,500
2011	ICES [22]	54.11	0.000408	1,924,000	1,443,000
2012	ICES [23]	42.12	0.000374	2,408,000	1,806,000
2013	ICES [24]	53.31	0.000376	2,298,000	1,723,500
2014	ICES [25]	48.02	0.000383	2,020,000	1,515,000

Fig. 2. Comparison of percentage of the potential for smolt production capacity (PSPC) attained in the steady state with salmon recruitment data from assessment years 2010–2014. The dashed line indicates the generic 75% of PSPC target suggested by the ICES.

target MEY enhances the reproductive capacity of the salmon stock while also providing higher profits for the fishers. In MEY, fishing costs make the fishing effort an essentially scarce resource, and putting more effort into fishing also increases the costs, i.e., the price of effort. This is why the effort is usually lower under MEY compared to the effort under MSY. Under MSY, the only limiting factor to fishing activity is the size of the fish stock, whereas fishing effort is not considered costly at all. Thus, aside the size of the stock, in MSY management all factors affecting fishers' behaviour are disregarded.

The sensitivity analysis of MEY management showed that increased prices and decreased costs improve the economic performance of the fishery but diminish the reproductive capacity of the salmon stock. The inherent uncertainty in assessing the stock-recruitment data is reflected in both the results of MSY and MEY management. Our results show that the relative economic tradeoff between MSY and MEY is highest when the productivity of the fish stock is high. In this situation, the efficiency of effort decreases considerably under MSY management. Thus society loses the most from targeting MSY when the productivity of a salmon stock is high.

Our results provide an example of optimized fisheries management. These results can be used for linking the economic viability and

ecological sustainability in managing the coastal salmon trap net fishery, which has recently become the most important commercial salmon fishery in Finland. In the literature, MSY is traditionally juxtaposed with MEY, which is unnecessary in our opinion as the objectives could be used as complements to capitalize on the best features of each of them. While targeting MEY, MSY could be used as an ecological limit if the economic realities would suggest smaller stock sizes than MSY management, that is, when MEY would no longer result in a state of the stock that is "above MSY". MSY has an important role as a limit target and can be used as a constraint for the MEY advice in an apparently relatively rare situation of high fish prices, exceptionally low fishing costs or a high discount rate, which are conditions that could lead to a stock collapse under MEY management. Based on the modelling results, aiming for MEY and keeping MSY at hand is proposed, as also suggested by Voss et al. [54] who introduce an ecologically-constrained Maximum Economic Yield (eMEY) in the case of the eastern Baltic cod fishery. Such a holistic approach would be a step towards the ecosystem-based management as well as reaching the goals set in the EU Blue Growth Strategy.

Since the salmon fishing quota is set for the commercial fisheries only, the model in this paper considers the optimization of commercial trap net fishing while considering the biological effects of recreational fishing. However, the optimal management of sequential salmon fisheries has been analysed by, e.g., Kulmala et al. [31], showing that a reallocation of harvest from offshore to coast and river would entail 70% larger benefits in the case of the Simojoki river salmon stock. These results are supported by Laukkanen [32], who shows that fisheries management could be improved to harness the full productive potential of the Northern Baltic salmon fishery by moving away from offshore fishing. The formerly dominating offshore fishery now contributes to a much smaller proportion of salmon catches. The ongoing reallocation of effort has also led to a shift towards harvesting salmon that spawn or are stocked within the country's own territory. This shift to a more clearly defined ownership of the salmon resource reduces the occurrence of strategic behaviour among the sequential fisheries that would otherwise require costly cooperation and negotiation efforts [33,43]. Modelling the economic dynamics of professional and recreational fisheries within the context of MSY and MEY is left for further study.

The scientific foundation for providing the management recommendations is still largely based on biological modelling of the fish stocks. Our modelling approach is an example of coupling economic and ecological systems in a fairly simple single-stock fishery. This type of integrated modelling is not yet an established tool in supporting management decisions, although it can provide invaluable information on the sustainability and profitability of marine resource use. The ICES working group on integrating ecological and economic models was organized in 2015, and provides a promising platform for integrating bioeconomic modelling with stock-assessment models. As marine fishing is an essential element of integrated coastal management, consideration of the socio-cultural impacts and values of fish, fishing and fisheries management (see e.g. [28,47]) would be a natural extension to the existing model. This could be done by e.g. relaxing the assumption

Table 4

Economic sensitivity analysis results under MEY. The 75% of PSPC target level is 1.72 million smolts according to the stock-recruitment data from assessment year 2013.

	Summed discounted net present value over time (M€)	Commercial annual harvest in number of fish at steady state	Optimal steady state annual effort in geardays	Annual number of smolts at steady state (in millions)
Salmon wholesale prices				
- 10% / + 10%	9.05 / 15.16	32,065 / 34,893	36,573 / 43,094	1.638 / 1.573
- 20% / + 20%	6.33 / 18.46	29,833 / 35,810	32,373 / 45,682	1.679 / 1.546
- 30% / + 30%	3.92 / 21.9	26,526 / 36,518	27,130 / 47,941	1.725 / 1.522
Unit cost of effort				
- 10% / + 10%	13.9 / 10.24	35,007 / 36,918	43,400 / 32,234	1.570 / 1.635
- 20% / + 20%	16.12 / 8.65	36,186 / 30,661	46,849 / 33,861	1.534 / 1.664
- 30% / + 30%	18.48 / 7.22	37,208 / 28,977	50,456 / 30,912	1.496 / 1.692
Discount rate				
- 40% / + 40%	18.42 / 8.48	33,096 / 34,189	38,756 / 41,297	1.617 / 1.591
- 60% / + 60%	23.65 / 7.31	32,764 / 34,412	38,032 / 41,852	1.624 / 1.585
- 80% / + 80%	31.21 / 6.38	32,403 / 34,619	37,268 / 42,378	1.631 / 1.580

of perfect malleability and giving a monetary value to both the non-market benefit of traditional fisheries' existence and the salmon stock as part of natural heritage to analyze the employment effects and implications to the fishing communities and to reconcile the effects of sudden reductions in fish stock, harvest and effort. Further integrated assessment and collaborative decision making could be developed by involving fishers, scientists, NGOs and policy makers as has been done in the MEY based management of Australian Commonwealth fisheries [37].

The single-stock modelling approach could be extended from Tornionjoki river stock to consider the whole Baltic salmon stock that is essentially characterized by multiple river stocks with varying productivities. The optimal effort resulting from a mixed-stock fishery optimization model is expected to be somewhat lower than the single-stock optimum reported in this paper, because Tornionjoki river stock represents one of the highest productivities among the Baltic stocks. In case the fisheries management efforts across the Baltic Sea were not coherent, a game theoretic modelling approach could be used to analyze the effects of one country applying MEY management, while other countries stick to the MSY management. Additionally, it should be noted that the model builds on constant cost and price functions, and

exploring the effects of alternative functional forms and extending the price portfolio to consider fish processing would give new insight into the economic and ecological dynamics of the fishery system. These extensions are left for future studies.

Declaration of interest

None.

Appendix A

The stock dynamics of salmon are modelled by mimicking as closely as possible the ICES salmon assessment model [39,40,41]) used for giving scientific advice that is required by the EU CFP. To predict the salmon population dynamics, an age-structured matrix model, sometimes referred to as the Leslie model, is used building on the salmon model first used in Holma et al. [17]. The original ICES stock assessment model is modified to consider the wild salmon stock and to accommodate the matrix modelling approach. The model is parametrized for the Tornionjoki river stock utilizing the ICES stock assessment results (Tables A.1 and 3).

Salmon are classified into $i \in \{1,…,10\}$ age groups. The salmon life history model is constructed as follows to calculate the number of salmon that have survived the offshore longline fishery at time $t + 1$ in the Main Basin before the spawning run:

$$\mathbf{s}_{ob,t+1} \qquad \mathbf{A}_{ob,t} \qquad\qquad\qquad \mathbf{s}_{ob,t}$$

$$\begin{pmatrix} s_{1,t+1} \\ s_{2,t+1} \\ \vdots \\ s_{i-1,t+1} \\ s_{i,t+1} \end{pmatrix} = \begin{pmatrix} FEC_1 & FEC_2 & \dots & FEC_{i-1} & FEC_i \\ SUR_1 & 0 & \dots & 0 & 0 \\ 0 & SUR_2 & \dots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \dots & SUR_{i-1} & 0 \end{pmatrix} \begin{pmatrix} s_{1,t} \\ s_{2,t} \\ \vdots \\ s_{i-1,t} \\ s_{i,t} \end{pmatrix},$$

where the vector $\mathbf{s}_{ob,t+1}$, containing the number of individuals in each age class i at time $t + 1$, is determined by the population projection matrix $\mathbf{A}_{ob,t}$ multiplied by the vector $\mathbf{s}_{ob,t}$, containing the number of age i individuals at time t. Salmon stock dynamics are specific to the management objective, $ob \equiv$ {MEY or MSY}. The biological and fishery related parameters and the elements of $\mathbf{A}_t$ are presented in Tables A.1 and A.2. In the matrix $\mathbf{A}_t$, the element FEC_i is the per capita fertility of age class i, and SUR_i is the age specific survival rate at age i. The ICES stock assessment model does not specify the life stages from spawned eggs to smolts emigrating the river on average 4 years after the spawning year. Instead, a Beverton-Holt stock-recruitment model is established to capture all the biological processes within this stage of the salmon life cycle. To follow the approach and to capture the time-delay effect in the stock dynamics of our model, the survival of the first four salmon life-stages is set to 1. The offshore longlining and river fishery enter the population dynamics as constant age-specific mortalities (OLL_i and rec_i) in the matrix A_t.

See Appendix Tables A1 and A2.

Table A.1

Initial population size and biological parameters for salmon [25].

Symbol	Value	Description (unit)
$s_{i,1}$	[175,600 175,600 175,600 175,600 1192.5 107.1 59.73 22.375 5.774 2.34]	Initial stock at $t = 1$ (1000 fish)
z_i	[0 0 0 0 0.02 0.5 0.5 0.5 0.5]	Sex ratio (prop. of females)
y_i	[0 0 0 0 0 0.1627 0.3446 0.537 0.467 1]	Maturation (prop. of spawners)
q_i	[0 0 0 0 0 0.00001411 0.00001325 0.00001325 0.00001325 0.000002851]	Commercial fishery catchability
fe_i	[0 0 0 0 0 3929 9142 13100 13650 17220]	Eggs per female
rec_i	[0 0 0 0 0 0.837067 0.824833 0.824833 0.824833 0.824833]	River fishery escapement
cw_i	[0 0 0 0 0 1.919 6.104 10.999 10.763 12.983]	Average catch weight[a] (kg)
OLL_i	[0 0 0 0 0 0.001958 0.11381 0.09637 0.09559 0.1015]	Median offshore longline survival
α	53.31	Beverton-Holt Recruitment parameter for year 2013
β	0.000376	Beverton-Holt Recruitment parameter for year 2013
$PSPC$	2298000	PSPC median for year 2013
ρ	0.75	Target level of PSPC
m_{ps}	0.1253	Proportional post-smolt survival (year^{-1})
m	0.949	Proportional natural adult survival (year^{-1})
m_{ins}	0.052	Instantaneous natural adult mortality
m_{seal}	8.4427	Instantaneous seal mortality (July & August)
m_S	$\frac{5m_{ins}}{6} + \frac{m_{ins}}{6m_{seal}}$	Instantaneous natural mortality for spawners
m_{74}	0.9625	M74 –syndrome survival[b] (year^{-1})

[a] The average catch weight of salmon takes into account the returning spawners, which makes the 4 and 5 sea winter salmon (age classes $i = 9$ and 10) relatively slimmer.

[b] M74 syndrome is a reproduction disorder typical for salmon stocks in the Baltic Sea that causes high mortality in hatched fry [29].

Table A.2

Elements of the life history matrix A_t.

Element	Description	Unit
$FEC_{i,t} = fe_i z_i y_i e^{-q_i E_{ob,t} - mS - rec_i}$	Fecundity $i \in \{1, \dots, 10\}$	Eggs per female
$SUR_{j,t} = 1, j = 1\dots3$	Survival assumed to be 1 for ages 1–3	
$SUR_{4,t} = \frac{m_{74}}{(\alpha + \beta s_{4,t}/1000)m_{74}}$	Recruitment with given M74 survival	Number of smolts
$SUR_5 = (1 - y_6)m_{ps}OLL_6$	Post-smolt survival at Baltic Main Basin	Number of salmon
$SUR_{g,t} = (1 - y_k)mOLL_k, g = 6\dots10, k = g + 1$	Adult survival at the Main Basin	Number of salmon

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