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ARTICLE

Consumer preferences for sustainably sourced seafood: Implications for fisheries dynamics and management

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Abstract

Many fish consumers reveal a preference for sustainably sourced seafood in their purchasing decisions. We propose a bioeconomic modeling approach and an empirical strategy, based on a discrete choice experiment, to quantify the resulting effects on fishery dynamics and to derive implications for efficient fishery management. We show that a "consumer stock effect" arises, which stabilizes a fishery under open access and which decreases catches under economically efficient management. We quantify these effects for the Western Baltic cod fishery.

KEYWORDS

bioeconomic model, discrete choice experiment, fisheries, renewable resource management, sustainability label

JEL CLASSIFICATION

Q11, Q22

1 | INTRODUCTION

Worldwide, fish and fishery products form an important source of protein and income for millions of people (FAO, 2024). However, increasing exploitation as well as environmental stressors pose serious threats to fish stocks, and the percentage of global stocks being classified as overused by the FAO has been increasing for decades (FAO, 2024). Fish consumers are aware of this and increasingly pay attention to the sustainability of the fisheries in their purchasing decisions (Asche & Bronnmann, 2017; Bronnmann et al., 2021; Bronnmann & Asche, 2017; Zheng et al., 2021). Accordingly, seafood labels such as the Marine Stewardship Council (MSC) label are gaining traction, with nearly 20% of global fish catches being MSC certified (MSC, 2024). Ecolabeled seafood can receive a substantial price premium, showing that consumers are willing to pay more for fish from a sustainability-certified fishery (Asche et al., 2015; Asche & Bronnmann, 2017; Bronnmann et al., 2021; Hori et al., 2020). This higher willingness to pay is mostly motivated by a concern for stock status and environmental impact of fishing (Bronnmann et al., 2021). However, in the current markets, the potential of sustainable fish products is not fully exploited (Altintzoglou & Nøstvold, 2014; Brécard et al., 2009; Pieniak et al., 2013).

According to bioeconomic theory, the fact that fishing costs decrease with fish stock size results in increases in the size of the fished population in steady state, both under open access and under economically optimal harvesting (Clark & Munro, 1975; Hannesson, 2007). This so called "stock effect" results in the conclusion that the "maximum economic yield" stock size, that is, the economically optimal stock size in the long run without discounting, is larger than the stock size that would generate the maximum sustainable yield (Clark, 1991; Clark & Munro, 1975; Grafton et al., 2007; Hannesson, 2007), which considers yield alone but disregards harvesting costs. Here, we discuss a new variant of stock effect, which arises as the value of fish increases with a larger (more sustainable) stock status. This is justified with the higher willingness to pay of consumers for fish from sustainable fisheries, leading to an upward shift of demand if the stock size is in a health shape. We call this effect the "consumer stock effect."

We develop and apply a bioeconomic model that seamlessly integrates the statistical analysis of stock assessment data and a demand model that is based on both time series of market price data and choice experiment data on preferences for different attributes of fish products. We assess the role of the consumer stock effect by contrasting results of model variants with and without considering the consumer stock effect, both in a setting of open access and under economically optimal fisheries management. We also quantify the resilience of the steady state in an open access setting by computing the characteristic time to approach the steady state (Pimm, 1984).

As a case study, we quantify the model based on detailed data for the Western Baltic cod fishery. This stock is attracting high interest, in particular recently, as it is outside safe biological limits (ICES, 2022a, 2022b; Möllmann et al., 2021; Voss et al., 2021). The bioeconomic model we develop for the Western Baltic cod fishery is based on Tahvonen et al. (2018). To be as close as possible to actual fisheries management, we use a single species age-structured fish population model, following the standard ICES (2022a, 2022b) stock assessment, and discuss sustainability reference points based on the scientific advice from ICES (2022a, 2022b). Currently, the Western Baltic cod fishery is best described as a restricted open access fishery: The fishery is subject to a number of input restrictions, including limited entry, gear restrictions, and seasonal closures. Yet, quotas have not been sufficiently restrictive in the past. For the German fleet, the actual catches have been considerably lower than the fishing quota for 9 out of the 10 years in the period 2012–2022 (ICES, 2022a, 2022b). This indicates that it has not been profitable for the fishermen to fully exhaust the quota (Quaas & Skonhoft, 2022). One reason might be a consumer concern for the sustainability of marine fisheries, which is prevalent among German fish consumers (Asche & Bronnmann, 2017; Bronnmann et al., 2021; Bronnmann & Hoffmann, 2018). The reduced demand from consumers may have reduced the incentives to continue fishing on the already overfished stock. At the same time, this consumer concern for sustainability may provide an extra economic reason to rebuild the stock. The aim of this paper is to quantify these effects for both settings, (restricted) open access and optimal management, for a real-world fishery.

For the case of the Western Baltic cod fishery, we find that the implications of the consumer stock effect are of large magnitude in the (restricted) open access fishery and would have significant implications for optimal fisheries management. We find that the stronger the consumer preferences for fish stock sustainability is, the lower is the characteristic time to approach the steady state, implying a higher resilience. Whereas the characteristic time with the consumer stock effect estimated from the data of the actual fishery is about 5 years, the hypothetical characteristic time without a consumer stock effect would be more than 25 years, that is, more than five times longer. However, we also find that the consumer concern for seafood sustainability is not sufficient to achieve an efficient outcome of the fishery without proper regulation. Rather, the economically optimal management should take the consumer concern for stock status into account. At any given fish population size, the efficient catches with the consumer stock effect are lower than the actual catches under open access and also than the catches that would be efficient without a consumer stock effect. Whereas the efficient catches without a consumer stock effect would be close to maximum sustainable yield management, the efficient catches that take into account the consumer stock effect are less than half as large. These quantitative results are obtained for the special case of the Western Baltic cod fishery, and uncertainties in both stock assessment and empirical quantification of consumer preferences translate into uncertainties in the magnitude of results. Yet, at least for this fishery, our results suggest that fisheries management that adequately reflects consumer preferences for sustainably sourced seafood should be more conservative than current management.

2 | RELATED LITERATURE

We build on the extensive literature that studies how the management of living resources should take into account use and non-use values of the ecosystem. In this literature, the non-use values are often attached to stocks that are different from the harvested resource itself. Armstrong et al. (2017) include the value of habitat in a bioeconomic analysis of fishing with gears that are destructive versus fishing with gears that are nondestructive to cold-water corals. The stock with non-use benefits, in this case, are cold-water corals, whereas the harvested resource is the fish population. Using data from a choice experiment and a bioeconomic model for the Northeast Arctic cod fishery, they show that the non-use value of cold-water corals for the Norwegian general population strongly affects optimal fishing activities. Ansuategi et al. (2019) consider local communities fishing on a shrimp stock in Baja, México, and nature-based tourism, in particular whale-watching trios, as a non-extractive activity. They show that fishing activity moderately decreases with the stock size of the whale population.

Similar in spirit to our paper but considering other types of natural resources are Manning et al. (2020) and Enriquez and Finnoff (2021). In both of these studies, it is the stock of the harvested resource that has a non-use value. Manning et al. (2020) use results from a dichotomous choice contingent valuation survey in an integrated assessment model of groundwater use in Kansas. They use this approach to estimate the value of a water right retirement program that aims at increasing the stock of groundwater. Enriquez and Finnoff (2021) develop a bioeconomic model for hunting and conservation of grizzly bears in the Greater Yellowstone Ecosystem, including non-use values of the grizzly bear population as well as damages from bear–human conflicts that increase with the grizzly-bear population. Enriquez and Finnoff (2021) build on the broader literature on "multi-use" wildlife populations, which analyzes how to manage populations that are both a value and a nuisance on a more conceptual level (Rondeau, 2001), including African elephants (Horan & Bulte, 2004), moose in Norway (Skonhoft & Olaussen, 2005), and the red king crab in the Barents Sea (Skonhoft & Kourantidou, 2021).

Most closely related to our paper are Bulte and Kooten (1999), Arnason (2008), and Kersulec et al. (2024), as they consider the management of a living marine resource, which at the same time has a consumptive value from harvesting and a non-use value attached to the stock. Bulte and Kooten (1999) integrate non-use benefits of preserving the stock of minke whales in a bioeconomic analysis of harvesting these whales for their consumption value. They find that including the non-use value substantially increases the optimal steady-state whale population size. Bulte and Kooten (1999) consider the preservation value of whales as a pure public good, and accordingly the objective function is additively separable in the consumption benefit and non-use value of whales. In contrast, the consumer preferences for sustainably sourced seafood, considered here, is a private value of a more healthy stock size, which shifts the demand function for resource harvest up or down. Arnason (2008) includes "conservationists," who only care about the stock status, as one stakeholder group in the analysis of optimal fisheries management, and studies the efficiency of an individual transferable quota system in this setting. Here, we focus on consumers of the resource who have a preference for consuming fish from a sustainably managed stock. Kersulec et al. (2024) study how consumer preferences affect the sustainability of a coastal multispecies fishery in French Guiana. They consider the demand model proposed by Quaas and Requate (2013) and use it to derive conditions for biologically sustainable consumer preferences while at the same time maintaining viable economic profits. We differ from Kersulec et al. (2024) as we explicitly derive demand for fish from a discrete choice experiment, which takes into account stock status of the resource.

In many studies that consider environmental preferences, the direct use value from harvesting and the non-use value from the ecosystem stock enter the societal objective linearly. This implies that under open access, when the non-use value is an externality in the decision making of resource harvesters, it has no effect on resource dynamics. In contrast, our focus is on the non-use value that directly interacts with the use value, as consumer willingness to pay for resource consumption increases with the resource stock size. This interaction between use value and non-use value has an effect on resource dynamics also under open access, as changes in the resource stock size affect the value of resource harvest. Under economically optimal management, the interaction between use value and non-use value has a nontrivial effect, as it affects not only the value of the stock but also demand for resource harvest.

This is an effect on the demand system that comes in addition to the usual downward-sloping demand. A downward-sloping demand function means that consumers are willing to pay a relatively high price if fish is getting scarce. In an open-access fishery, this implies that incentives to catch remain relatively high if the stock is decreasing. This effect may be strong enough that the fishery becomes unstable at low stock sizes (Dao et al., 2023; Holden & McDonald-Madden, 2017; Quaas & Requate, 2013; Smith, 1969), and it also tends to decrease economically optimal harvest at high stock sizes (Zimmermann et al., 2011b). Our analysis takes this effect into account and therefore includes both effects: Demand is a decreasing function of the fish quantity available on the market and also an increasing function of the current size of the fish population size.

Our study also builds on previous work that includes a positive effect of fish population size on seafood demand in bio-economic analysis. These studies come to similar conclusions as we do but for reasons other than a consumer concern for fish stock sustainability. Several studies include the effect that the quality of landed fish is increasing with the fish stock size, which increases the market price that consumers are willing to pay. One aspect is that larger fish of the same species get a higher market price (Quaas et al., 2013; Zimmermann & Heino, 2013). Zimmermann et al. (2011a) show that this effect reduces harvest rates and implies a larger optimal stock size. World Bank (2016) present a bio-economic model of the global marine fisheries, where the fish price is an increasing function of fish biomass. This is supposed to capture the effects that a larger global fish population biomass also means that landings increasingly consist of more valuable species and larger individual fish, which get a higher market price, as also discussed in Grafton et al. (2005) and Costello et al. (2016). These effects amplify the benefits of more effective fisheries management. We use exactly the same formulation of the demand model as World Bank (2016) but in a single-species age-structured population model, with the aim to capture a consumer concern for sustainably sourced seafood, not an increasing quality of the seafood product itself. Whereas this distinction does not matter for general theoretical results, it is important for the quantification of the effects, which is the main purpose of the present paper.

3 | THEORY

3.1 | Model of seafood demand with consumers caring for stock status

We consider a representative consumer making a choice over the quantity q of seafood consumption, which may depend on the stock size (or stock status) B and on a vector of other characteristics

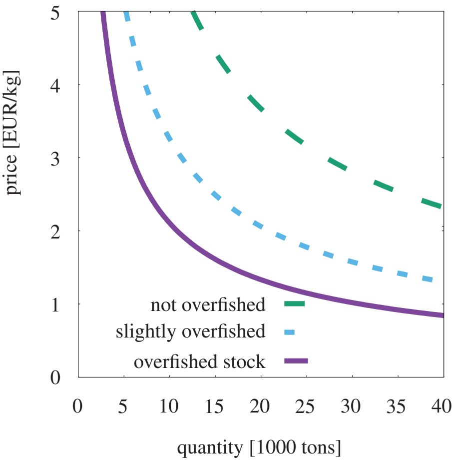


FIGURE 1 Demand function for cod for three levels of the stock status: overfished ($\boldsymbol{B}_{\mathbf{lim}}$), slightly overfished ($\boldsymbol{B}_{\mathbf{pa}}$), and not overfished ($\boldsymbol{B}_{\mathbf{msy}}$) – of Western Baltic cod.

of the fishery $\boldsymbol{A}$, in addition to the fish price p. The consumer has a budget m available for the consumption of fish and the numeràire z, that is, a composite good of price normalized to one, so that $m = p \cdot q + z$. We specify an iso-elastic inverse demand function

$$P(q) = a\boldsymbol{A}^{\chi} B^{\sigma} q^{-\eta}. \tag{1}$$

In this equation, B denotes stock biomass, with σ being the stock elasticity of demand; q denotes the quantity of fish consumption, and accordingly, η denotes price flexibility. Given $\eta > 0$, the demand function (1) has the usual downward-sloping property. We further assume $\eta < 1$, which means that expenditures increase with the consumed quantity. Finally, $a\boldsymbol{A}^{\chi} > 0$ is a demand shifter that captures potentially observable as well as unobserved effects on demand, including other fishery-related variables $\boldsymbol{A}$ the consumer may care about, which enter with an elasticity χ. Whereas the empirical analysis requires us to specify the demand function, such a specification naturally comes with restrictions. One is that the iso-elastic form can only be regarded as an approximation over a limited interval of prices and quantities of fish consumption. Second, the iso-elastic relationship of the demand shifter on the variables of interest may also become problematic if these variables exceed certain limits. Third, a multiplicative demand shifter implies a particular complementarity between stock status and consumed quantity, such that the effect of the demand shift—in absolute quantities—is particularly large as the consumed quantity is small.

The introduction of the demand shifter allows capturing demand effects of credence attributes of the fish such as the sustainability of the fishery. In our case, we use the demand shifter to capture preferences for a healthy stock. As found for example in Bronnmann et al. (2021), demand shifts upward if the product comes from a fishery with a healthy stock (Figure 1, using data for the case of Western Baltic cod).

The demand function (1) implies an indirect utility function, which can be derived using Roy's Identity under the assumption of constant income elasticity. Specifically, we integrate (1) to obtain (see online Appendix S1)

$$V(p,A,B) = m + \frac{1}{1-\eta}\left(a\boldsymbol{A}^{\chi} B^{\sigma}\right)^{\frac{1}{\eta}} p^{1-\frac{1}{\eta}}. \tag{2}$$

In this equation, m is a constant of integration that captures all effects on utility not directly interacting with fish consumption. This includes income, as we have to ignore income effects in the model, due to lack of data.

3.2 | Fishery economic behavior

Fishers are assumed to maximize profits, taking as given market prices, fishing technology, and regulatory constraints. Using H_t to denote total catches and B_t to denote fish population biomass in year t, we model the fishing cost function as

$$C(H_t,B_t)=\frac{c}{1+\varepsilon}\frac{H_t^{1+\varepsilon}}{B_t}. \tag{3}$$

Here, $c>0$ is a cost parameter, which possibly includes the costs of technical constraints, such as mesh size restrictions or seasonal closures, and $1+\varepsilon>1$ is the elasticity of the fishing cost function with respect to catch. This captures an effect that unit fishing cost increase with harvest H_t due to congestion externalities (Smith, 1969).

The cost function specified in Equation (3) also features the classical stock effect that fishing costs decrease with increasing stock size B_t (Clark & Munro, 1975; Hannesson, 2007), which is a sensible assumption for a search fishery, as the Western Baltic cod fishery is. For the purposes of model identification and having lack of more precise information on cost elasticity with respect to stock size, we assume that the unit fishing costs are inversely proportional to fish population biomass. We note that this is a restrictive assumption, which possibly overestimates the classical cost-based stock effect, as this elasticity may differ from (minus) one (Steinshamn, 2011), and also that we ignore any (quasifixed) costs that are independent of the harvest and biomass.

3.3 | Fish population dynamics

We consider an age-structured population model with S age classes, using the notation of Tahvonen et al. (2018), where x_{st} denotes the stock numbers of age s in year t, and α_s the survival rate from age s to age $s+1$. Recruitment at age 1 is given by the stock-recruitment function $\varphi(x_{0t})$, which models recruitment as a function of spawning stock biomass x_{0t}. Spawning stock biomass is defined as

$$x_{0t}=\sum_{s=1}^{S} w_s\gamma_s x_{st}. \tag{4}$$

In this equation, w_s is the average weight of an individual of age s and γ_s is the fraction of fish of age s that is mature.

Using h_{st} to denote the harvest of fish aged s in year t, the population dynamics can be summarized as

$$x_{1,t+1}=\varphi(x_{0t}) \tag{5a}$$

$$x_{s+1,t+1}=\alpha_s x_{st}-h_{st} \qquad \text{for } s=1,\ldots,S-1 \tag{5b}$$

$$x_{S,t+1}=\alpha_{S-1}x_{S-1,t}+\alpha_S x_{St}-h_{St}. \tag{5c}$$

We use S to denote the oldest age class. For the case of Western Baltic cod we specify $S = 7$ years, following the ICES (2022a, 2022b) stock assessment. Following Tahvonen et al. (2018) and Stoeven et al. (2021), the number of fish that is harvested from age s is given by

$$h_{st} = q_s \frac{H_t}{B_t^e} x_{st}. \tag{6}$$

The constants q_s denote age-specific catchability coefficients. These constants depend on mesh size, which we consider to be fixed. Moreover, $H_t := \sum_{s=1}^{S} w_s h_{st}$ is aggregate catch, and $B_t^e := \sum_{s=1}^{S} q_s w_s x_{st}$ is the "efficient biomass" (Tahvonen et al., 2018; Zimmermann & Jørgensen, 2015), such that H_t / B_t^e can be interpreted as the exploitation rate of the fishery in year t.

3.4 | Fishery dynamics under open access

One of the two management scenarios we consider is (restricted) open access: the fishery is subject to technical regulations such as gear restrictions and seasonal closures but without an effective quota management (Quaas & Skonhoft, 2022; Reimer & Wilen, 2013). The technical regulations effectively increase (marginal) fishing costs, and only this is restricting catches compared to pure open access. We refer to this situation as restricted open access, or simply open access. Under restricted open access, the harvested quantity is determined by the zero-profit condition that the price equals fishing cost (Quaas & Skonhoft, 2022). Using the demand function (1) and the cost function (3), this condition becomes

$$aA^{\chi} B_t^{\sigma} H_t^{-\eta} = p_t = c B_t^{-1} H_t^{\varepsilon} \tag{7}$$

From this we obtain the fish catch under open access as a function of the current biomass,

$$H_t = \left(\frac{aA^{\chi}}{c} \right)^{\frac{1}{\varepsilon+\eta}} B_t^{\frac{1+\sigma}{\varepsilon+\eta}}. \tag{8}$$

Using (8) and (6) in (5a)–(5c), we can write the dynamics of the fish population harvested under open access in matrix form

$$\begin{pmatrix} x_{1,t+1} \\ \vdots \\ x_{s+1,t+1} \\ \vdots \\ x_{S,t+1} \end{pmatrix} = \begin{pmatrix} \varphi(x_{0t}) & 0 & \cdots & \cdots & 0 \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ 0 & \cdots & \alpha_s & \cdots & 0 \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ 0 & \cdots & \cdots & \alpha_{S-1} & \alpha_S \end{pmatrix} \begin{pmatrix} 1 \\ \vdots \\ x_{st} \\ \vdots \\ x_{St} \end{pmatrix} - \begin{pmatrix} q_1 \left(\frac{aA^{\chi}}{c}\right)^{\frac{1}{\varepsilon+\eta}} B_t^{\frac{1+\sigma}{\varepsilon+\eta}-1} x_{1t} \\ \vdots \\ q_s \left(\frac{aA^{\chi}}{c}\right)^{\frac{1}{\varepsilon+\eta}} B_t^{\frac{1+\sigma}{\varepsilon+\eta}-1} x_{st} \\ \vdots \\ q_S \left(\frac{aA^{\chi}}{c}\right)^{\frac{1}{\varepsilon+\eta}} B_t^{\frac{1+\sigma}{\varepsilon+\eta}-1} x_{St} \end{pmatrix}. \tag{9}$$

Here, x_{0t} is the spawning stock biomass (SSB; Equation 4), and B_t is total stock biomass.

The dynamics of the fishery under (restricted) open access can be simulated, starting from the current state described by the age-specific stock numbers in the transition toward a steady state. The eigenvalues associated with the Jacobian of (9) evaluated at steady state provide information about the stability properties of the steady state. If the steady state is asymptotically stable, the characteristic time at which the fishery approaches the steady state is given by the leading eigenvalue (Pimm, 1984).

3.5 | Fishery dynamics under economically optimal management

The second of the two management scenarios we consider is that of a fishery that is managed such as to maximize the present value of economic surplus, which is the sum of consumer and producer surpluses (Anderson, 1980; Copes, 1972; Jensen et al., 2019; Kroetz et al., 2022; Quaas et al., 2018). We refer to this as economically optimal or efficient management. Using δ to denote the social discount rate, the economically optimal catches H_t are determined by the solution to the dynamic optimization problem

$$\max_{\{H_t\}} \sum_{t=0}^{\infty} \frac{1}{(1+\delta)^t} \left(\frac{aA^{\chi}}{1-\eta} B_t^{\sigma} H_t^{1-\eta} - \frac{c}{1+\varepsilon} B_t^{-1} H_t^{1+\varepsilon} \right) \tag{10}$$

subject to fish population dynamics (5a)–(5c), given initial fish population size, and non-negativity constraints $H_t \geq 0$ and $x_{st} \geq 0$, $s = 1, \ldots, S$, $t = 0, \ldots$. Consumer surplus is derived from the demand function (1) or equivalently from the indirect utility function (2); producer surplus from the cost function (3). As expenditures for the consumers equal revenues for the fishers, they drop out from the welfare function. As the price of fish depends on harvest and biomass, which both are controlled in the optimal fishery, the objective entangles the positive effect of increasing catch and stock size for consumers and for fishers, who also benefit from higher prices.

We quantify the model parameters empirically using data for the Western Baltic Sea and solve the optimization problem (10) numerically. The time horizon is set to an arbitrary value long enough that a steady state is reached, and results are presented only for the period of the transition toward the steady state, which is after about 30 years. The numerical optimization is performed using the state-of-the art interior point algorithm implemented in Knitro (version 14.0) with AMPL (Byrd et al., 2006). Programming codes are provided in the online Appendix S1.

4 | DATA AND METHODS

4.1 | Population dynamics of Western Baltic cod stock

The cod population in the Western Baltic Sea has been subject to overfishing for many years and recently has been assessed as ecologically collapsed (Möllmann et al., 2021). According to the stock assessment by the International Council for the Exploration of the Sea (ICES), the stock has been for several years below the spawner biomass $B_{\lim}$ where recruitment starts to be impaired (ICES, 2022a, 2022b).

We quantify the parameters of the age-structured fish population model (5a)–(5c) based on the data provided by the ICES (2022a, 2022b) stock assessment report. The age-specific survival rates are computed from the age-specific mortality rates M_s, which are given in ICES (2022a, 2022b), as $\alpha = \exp(-M_s)$. Weights at age w_s, which are used to compute the biomass, and the age specific fractions of mature fish γ_s used to compute spawning stock biomass (4), are directly given in ICES (2022a, 2022b). Age-specific catchabilities q_s are derived from age-specific fishing mortalities estimated by ICES (2022a, 2022b), normalizing the fishing mortality for the largest fish to one. The specifications of these parameters can be found in the programming codes in the online Appendix S1.

For the stock-recruitment model, we follow ICES and assume that recruitment monotonically increases with spawning stock biomass if it is below $B_{\lim}$. In line with ICES (2022a, 2022b), $B_{\lim}$ is determined as the average of lowest SSB in years with above average recruitment (1990, 1991, 1993, 2016). The corresponding estimate for the Western Baltic cod fishery is $B_{\lim} = 15{,}067$ tons. According to the model used by ICES (2022a, 2022b), recruitment is constant above the limiting biomass $B_{\lim}$ and computed as the geometric mean of recruitment in all observations where the estimated biomass was above $B_{\lim}$. For the numerical computations, we use a "smooth hockey stick" stock-recruitment model (Froese et al., 2008)

$$\varphi(x_{0t}) = \phi_{\lim}\left(1 - \exp\left(-\phi_0 \frac{x_{0t}}{\phi_{\lim}}\right)\right). \tag{11}$$

In the stock-recruitment model, $\phi_{\lim} > 0$ is maximum recruitment, and ϕ_0 is the number of recruits per spawner at zero spawning stock size.

We use the maximum sustainable yield as the reference point for biological overfishing. ICES does not provide an estimate for the maximum sustainable yield. To derive the maximum sustainable yield from our cod population model, we first compute the equilibrium yield curve. Each point on the curve is computed by fixing the spawning stock biomass at a specified level and then maximizing equilibrium catch by choosing harvest and age composition, given the population model (5a)–(5c) in equilibrium, that is, when $x_{s,t+1} = x_{st}$. In this curve, which is shown in green in Figure 2, the maximum sustainable yield is at a spawning stock biomass $x_0^{\mathrm{msy}} = 63{,}140$ tons.

Unlike in the biomass framework, there is no unique definition of the maximum sustainable yield for an age-structured population. Tahvonen et al. (2018) show that for an age-structured population, the maximum sustainable yield depends on fishing technology. In particular, it is important how exactly yield depends on fish abundance. Tahvonen et al. (2018) propose that the *efficient biomass* B_t^e is the appropriate density measure, instead of the total stock biomass B_t, which we have used in the cost function (3). The efficient biomass is computed by weighting the biomass at each age by the age-specific catchability q_s. Using a model with efficient biomass in the cost function, we obtain a maximum sustainable yield spawning stock $x_0^{\mathrm{msy}} = 82{,}200$ tons. In the literature, there exist even higher estimates for the maximum sustainable yield biomass (Froese & Proelß, 2010). Given this uncertainty about what is the correct maximum sustainable yield stock size, we assume that

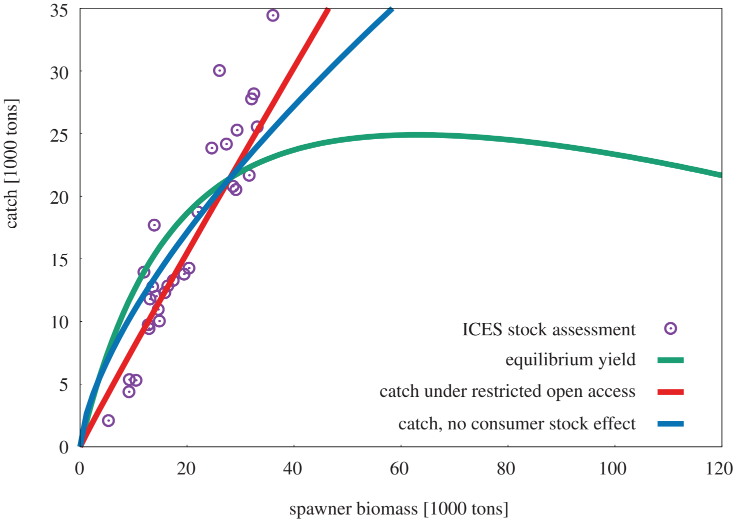


FIGURE 2 Phase diagram summarizing the dynamics of the Western Baltic cod fishery under restricted open access. The green curve shows the equilibrium yield of the fishery derived from the age-structured fish population model with fixed age-specific catchabilities. The dots show data from ICES (2022a, 2022b) stock assessment. The red curve shows the catch under restricted open access as simulated from the full bioeconomic model. The blue curve shows the catch under restricted open access in the hypothetical situation where consumer demand would not change with fish stock status.

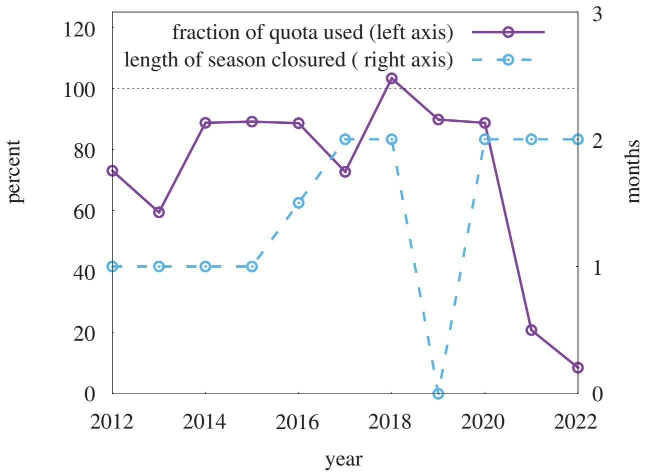


FIGURE 3 The figure shows the fraction of the quota used by German fishermen in the Western Baltic cod fishery, which is obtained by dividing the actual catches by the final quota, using data from the German Federal Office for Agriculture and Food. This indicates that in many years, the total allowable catches have not effectively constrained the fishery, as part of the quota has been left unused. At the same time, numerous technical restrictions have been in place such as closed seasons (shown in the figure) and gear restrictions, which have limited the profitability of the fishery.

consumers precautionarily consider the larger of our two estimates, namely $x_0^{\mathrm{msy}} = 82{,}200$ tons, as the reference point for assessing overfishing.

In line with the ICES (2022a, 2022b) advice and the management plan for Western Baltic cod, we take the value $B_{\mathrm{lim}} = 15{,}067$ tons as the threshold for a heavily overfished stock and the value $B_{\mathrm{msy}} = 82{,}200$ as the threshold for not overfished. In addition, ICES (2022a, 2022b) defines the "precautionary" biomass B_{pa} as the spawning stock biomass below which catches should be reduced. The precautionary biomass for the Western Baltic cod stock is estimated by ICES (2022a, 2022b) to be $B_{\mathrm{pa}} = 23{,}492$ tons. We use this as the threshold below which the stock would be deemed slightly overfished.

4.2 | Estimating the aggregate demand and cost function for the Western Baltic cod fishery

To estimate demand and cost functions at the level of the entire fishery, we follow the approach of Tahvonen et al. (2018) and assume that the model in a (restricted) open access setting, summarized in Equation (9), adequately describes the past dynamics for the Western Baltic cod fishery. This assumption is justified by the observation that the actual catch quotas have not been binding in most years of the past decade (see Figure 3), especially not in the last years when the stock size has been particularly low. Our interpretation of this observation is that fishing was not profitable beyond the observed amount: The zero-profit condition has constrained catches, not the total allowable catch.

Taking logs on (8), and allowing for a time trend (rate ξ) on harvesting costs, we obtain the first of two equations that can be estimated, which relates total catch and total biomass. Using this relationship again in Equation (7), we get a relationship between price and population biomass. When considering data on nominal prices $\tilde{p}_t$, we adjust for inflation by including a constant trend, $\tilde{p}_t = p_t \exp(-\imath t)$. We thus obtain the statistical model

$$\ln(H_t) = \beta_0^H - \beta_t^H t + \beta_B^H \ln(B_t) + \psi_t^H, \tag{12}$$

$$\ln\left(\tilde{p}_t\right) = \beta_0^{\tilde{p}} - \beta_t^{\tilde{p}}\, t - \beta_B^{\tilde{p}} \ln(B_t) + \psi_t^p, \tag{13}$$

with parameters specified in Table 1. We estimate two versions of the model, one where the error terms ψ_t^H and ψ_t^p are correlated, but uncorrelated over time, and another one where they additionally are temporally autocorrelated, following an AR(1) process.

For the model, we need to know seven parameters, namely four parameters of the demand function (i.e., the demand shifter $\widehat{a} := aA^{\chi}$, the stock elasticity of demand, σ, the price flexibility η, and the trend ι), and three parameters of the cost function (the cost parameter c, the elasticity ε, and the trend ξ). The statistical analysis allows us to estimate six coefficients.

Thus, we need further information to quantify the remaining parameter. We use the choice experiment for this purpose. Specifically, using the expressions for β_B^H and for $\beta_B^{\tilde{p}}$ in Table 1, the estimates from the fishery-level data imply the following relationship between the stock elasticity of demand and the price flexibility:

$$\beta_B^H \eta = \beta_B^{\tilde{p}} + \sigma. \tag{14}$$

When using data from the discrete choice experiment to estimate the consumer preferences for stock status, σ, we strive for an estimate that is consistent with the fishery-level estimates, that is, consistent with condition (14). We therefore impose restriction (14) when we estimate the model for the discrete choice experiment to obtain the stock elasticity of demand, σ, from the choice experiment data. Once σ is known, the remaining parameter values can be computed from the coefficients estimated using fishery-level data in Equations (12) and (13).

4.3 | Estimation of preference parameters from choice experiment data

The advantage of the choice experiment is that it allows us to disentangle the parameters that capture different aspects of consumer preferences. Here, we are particularly interested in the stock elasticity of demand, as this captures the consumer preferences for sustainably sourced seafood. Whereas we develop the procedure for the specific case of the Western Baltic cod fishery, the approach can be applied more generally. The assumption is that consumers choose the alternative that gives the highest indirect utility, as given in Equation (2).

In the choice experiment, participants are faced with multiple, yet independent and mutually exclusive, decisions over three alternatives $i \in \{1,2,3\}$. In our specific case, alternatives depict a typical purchase decision of 250 grams of frozen cod fillets (e.g., in a supermarket). The participant is asked to choose one of the alternatively offered cod fillets or opt out. The alternatively offered cod products differ in the fishery-related characteristics $\boldsymbol{A}_i$, the stock status B_i, and the fish price p_i. Thereby, the fishery-related observable variables $\boldsymbol{A}$ in the demand shifter $a\boldsymbol{A}^{\chi}$ include the fishing area, fishing gear, and bycatch. We further assume that a_i is a random component capturing unmeasured utility-relevant characteristics associated with any of the three choice alternatives $i \in \{1,2,3\}$: one of the two alternative cod products $i = 1,2$ or the opt-out alternative 3.

TABLE 1 Relationship between parameters in empirical model and the bioeconomic model parameters.

Description	Equation (14)			Equation (15)		
Parameter to be estimated	β_0^H	β_t^H	β_B^H	$\beta_0^{\tilde{p}}$	$\beta_t^{\tilde{p}}$	$\beta_B^{\tilde{p}}$
Model parameter	$\frac{\ln\left(\widehat{a}\right) - \ln(c)}{\varepsilon+\eta}$	$\frac{\xi}{\varepsilon+\eta}$	$\frac{1+\sigma}{\varepsilon+\eta}$	$\frac{\varepsilon \ln\left(\widehat{a}\right) - \eta \ln(c)}{\varepsilon+\eta}$	$\iota - \frac{\eta\xi}{\varepsilon+\eta}$	$\frac{\eta-\sigma\varepsilon}{\varepsilon+\eta}$

A consumer weakly prefers alternative k over any other alternative i if and only if

$$V\left(p_k, \boldsymbol{A}_k, B_k\right) \geq V\left(p_i, \boldsymbol{A}_i, B_i\right) \qquad \text{for all}\, i \in \{1,2,3\} \tag{15}$$

Using the expression (2) for the indirect utility function, this implies that the option k is the best choice for the consumer if and only if

$$\begin{aligned} &\chi \cdot \ln(\boldsymbol{A}_k) + \sigma \ln(B_k) + (\eta - 1)\ln\left(p_k\right) + \ln(a_k) \\ &\quad \geq \underbrace{\chi \cdot \ln(\boldsymbol{A}_i) + \sigma \ln(B_i) + (\eta - 1)\ln\left(p_i\right)}_{:= U_i} + \ln(a_i) \text{ for all } i \in \{1,23\}, \end{aligned} \tag{16}$$

and with U_i denoting the observable part of indirect utility derived from choice alternative i.

Assuming that all $\zeta_i := \ln(a_i)$ are extreme value type I independently and identically distributed, we can model the probability of a consumer choosing alternative k as

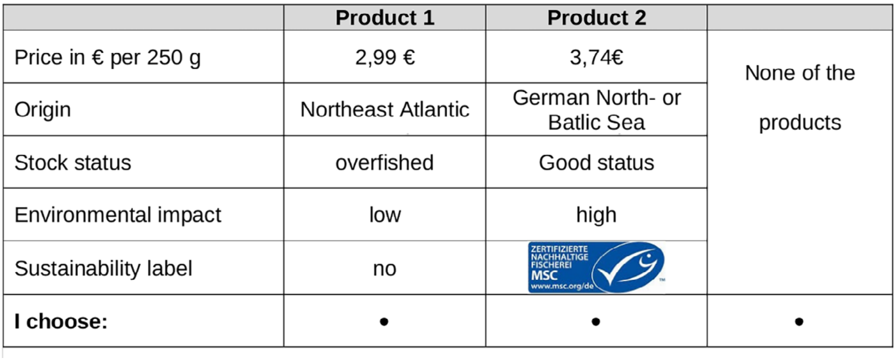
$$\text{Prob}(k) = \frac{\exp(U_k)}{\sum_{i=1}^{3} \exp(U_i)}, \tag{17}$$

which is the conditional logit model (McFadden, 1974). The parameters of the observable part of the indirect utility function can be estimated by maximizing the resulting log likelihood function

$$LL = \log\left(\prod_{n=1}^{N} \prod_{i=1}^{3} \text{Prob}(ni)^{d_{ni}}\right). \tag{18}$$

We set d_{ni} equal to one if alternative i is chosen by consumer n and zero if it is not chosen, such that $\prod_{i=1}^{3} \text{Prob}(ni)^{d_{in}}$ is the modeled probability of the alternative i chosen by consumer n.

To estimate the parameters of the demand function (1) that capture consumer preferences for sustainably sourced seafood, we use data from Bronnmann et al. (2021). Their choice experiment was part of an online survey with a final sample of $N = 1{,}453$ German fish-consuming households in November 2017. An example of a choice card shown to the respondents is shown in Figure 4. The two products were physically identical, 250 grams of frozen cod fillet, a typical fish product for



	Product 1	**Product 2**	
Price in € per 250 g	2,99 €	3,74€	None of the products
Origin	Northeast Atlantic	German North- or Batlic Sea	
Stock status	overfished	Good status	
Environmental impact	low	high	
Sustainability label	no	ZERTIFIZIERTE NACHHALTIGE FISCHEREI MSC www.msc.org/de	
I choose:	●	●	●

FIGURE 4 Example choice card in the discrete choice experiment with German fish consumers (Bronnmann et al., 2021).

German consumers. The price attribute varied in five levels around the actual mean price for this product. In addition, the experiment included five more attributes. The first attribute was the origin of the fish split into three levels: worldwide fishery, Northeast Atlantic, German North or Baltic Sea. Each of these include the Western Baltic cod fishery. The second attribute defined two alternative types of fishery, namely the large high-sea fishery or the artisanal coastal fishery.

The third attribute, stock status, is the one of main interest here. It was varied with three levels: overfished, slightly overfished, or good status. We identify these levels with stock biomass at $B_{\text{lim}} = 15{,}067$ tons, at $B_{\text{pa}} = 23{,}492$ tons, and at $B_{\text{msy}} = 82{,}200$ tons, consistently with the stock assessment for Western Baltic cod discussed above. The final attributes were environmental impact (i.e., bycatch of nontarget species), which took the levels of "high" or "low," and whether the product carried an MSC label. We allowed for cases where the environmental impact was high, and still the label was present, as this is consistent with biological evidence (Opitz et al., 2016).

5 | RESULTS

5.1 | Estimation of empirical model parameters

Using yearly time series data (32 observations for the period 1994 to 2021) on fish prices and catches from the German Federal Office for Agriculture and Food, and on stock biomass from ICES (2022a, 2022b), we estimate aggregate demand and supply according to Equations (12) and (13). The results for the models with and without temporal autocorrelation are presented in Table 2. All point estimates have the expected signs, and point estimates are robust to the considerations of temporal autocorrelation. However, when considering temporal autocorrelation, the point estimate for the log biomass in Equation (13) is not statistically significant. We consider this uncertainty in the sensitivity analysis.

Table 3 reports the estimated results of the conditional logit regression model on the data from the choice experiment. We estimated three specifications of the conditional logit model (17) that differ with respect to how stock status is defined. In model (A), we use dummy variables with *not overfished* as the baseline. In model (B), we use a continuous specification of cod stock, substituting the

TABLE 2 Estimates of Equations (12) and (13).

	Model (1)		**Model (2)**	
Variable	**Log catch**	**Log Price**	**Log catch**	**Log price**
	(Equation 14)	**(Equation 15)**	**(Equation 14)**	**(Equation 15)**
Intercept	−0.63***	1.04***	−0.55***	0.53**
	(0.17)	(0.27)	(0.18)	(0.24)
Log(biomass)	1.06***	0.24*	0.97***	0.25
	(0.06)	(0.10)	(0.12)	(0.16)
Time	−0.01***	−0.02***	−0.02***	−0.00
	(0.00)	(0.01)	(0.00)	(0.01)
AIC	−17.49		−32.25	
BIC	−8.701		−17.91	
Log likelihood	14.75		26.13	
Num. obs.	32		32	

Note: Model (1) allows for correlation of the error terms in Equations (12) and (13); model (2) additionally allows for temporal autocorrelation, modeled as an AR(1) process.
***$p < 0.01$; **$p < 0.05$; *$p < 0.1$.

TABLE 3 Regression results for conditional logit model on choice experiment.

Variable	Model (A) dummy	Model (B) continuous	Model (C) constraint
chosen			
Log(price)	−0.91***	−0.85***	−0.33***
	(−39.7)	(−37.7)	(−34.1)
Slightly overfished	−0.41***		
	(−17.1)		
Strongly overfished	−1.63***		
	(−53.9)		
EU fishery	−0.072**	−0.024	0.050*
	(−2.9)	(−0.95)	(2.1)
Worldwide fishery	−0.060*	0.014	0.093***
	(−2.3)	(0.55)	(3.7)
MSC	0.44***	0.38***	0.39***
	(19.4)	(17.1)	(18.0)
Bycatch	−1.12***	−1.00***	−0.74***
	(−44.9)	(−41.3)	(−34.8)
Alt 1 or 2	1.75***	1.66***	0.57***
	(35.5)	(34.0)	(23.9)
Stock size		0.73***	0.45***
		(49.0)	(44.8)
Observations	75,240	75,240	75,240
Pseudo R^2	0.12	0.11	
AIC	48,229	49,188	49,869
BIC	48,303	49,252	49,924
ll	−24,106	−24,587	−24,928

Note: *t* statistics in parentheses. Model (A) uses dummy variables for the three levels of the “stock status” attribute, model (B) uses a continuous variable for stock status. Model (C) is similar to model (B) with the constraint (14) implemented that makes the discrete choice model consistent with the market-level data.

$^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

levels from the choice experiment with the current levels from the ICES. Model (C) is similar to model (B) but imposes the restriction (14) derived above. Despite its lower statistical fit, we use model (C) in the following analysis, as it is consistent with the bioeconomic model, especially the constraint (14) imposed by the fishery-level observations. The point estimates show the expected sign in all three model specifications. The coefficient for the price is negative, and the coefficient for stock status is positive throughout the specifications. This is in line with our theoretical expectations: The cheaper the product and the larger the stock status is, the higher is the probability to purchase the cod fillet.

5.2 | Bioeconomic model

We use the bioeconomic model to analyze how the consumer preferences for sustainably sourced seafood changes the dynamics of the Western Baltic cod fishery in the two management scenarios of (a) restricted open access and (b) economically optimal management.

Contrasting fishery dynamics with and without consumer preferences for stock sustainability in open access, we first contrast the fishery dynamics of the Western Baltic cod fishery for the actual management regime, which is best characterized as restricted open access (Quaas & Skonhoft, 2022), for the actual demand function and for a hypothetical demand function without a consumer preferences for sustainably sourced seafood.

The results are shown as a phase diagram (Figure 2), plotting catches and biological growth as functions of spawning stock biomass. The green curve shows the equilibrium yield of the fishery. This curve is not symmetric as it would be in a standard logistic growth equation, but rather, it shows a typical skewness with a slow decrease of equilibrium yield at high stock sizes. The dots in Figure 2 show data from ICES (2022a, 2022b) stock assessment. The red curve shows the catch under restricted open access as simulated from the full bioeconomic model, as summarized in Equation (9). As the model is estimated from the data under the assumption of restricted open access, it is no surprise that the model closely follows the data.

The blue curve shows the catch under restricted open access in the hypothetical situation where consumer demand would not change with fish stock status. The demand shifter for this model variant is calibrated such that the steady state is the same as for the full model. The blue curve that shows the catch without consumer preferences for sustainability has a strikingly different shape from the model with the feedback from stock status to demand. In particular, catches would be much lower at high stock sizes and much higher at small stock sizes, as prices would be rather high. The overall result is that the fishery would have been much less resilient if the effect of consumers decreasing demand in response to declining fish population was not present.

To more rigorously explore this effect of consumer preferences for seafood sustainability in the restricted open-access fishery, we consider the dynamics as described by (9) in the neighborhood of the steady state. The steady state is asymptotically stable if all eigenvalues of the Jacobian have real parts that are less than one in absolute value. In particular, stability requires that the largest of the negative eigenvalues (i.e., the smallest in absolute value) is still smaller than one (in absolute terms). Pimm (1984) proposes to measure the resilience by this largest eigenvalue. The smaller it is, the more resilient is the steady state of the fishery under restricted open access. Somewhat more intuitive is to compute, from the largest eigenvalue, the characteristic time at which the fishery asymptotically approaches the steady state. The larger the characteristic time, the less stable the steady state is.

We measure the consumer preferences for seafood sustainability by the elasticity σ at which demand increases with stock size. Empirically it is $\sigma = 0.45$ for cod. We ask how the stability of the steady state, as measured by the characteristic time, changes with σ, keeping the steady-state fish population size constant.

The results are shown in Figure 5. We find that the stronger the consumer preferences for a healthy stock status, that is, the larger the stock elasticity of demand, σ, the faster is the characteristic time at which the fishery approaches the steady state. In particular contrasting the actual fishery with $\sigma = 0.45$ to a fishery without the consumer preferences for sustainable sourced seafood, $\sigma = 0$, the characteristic time to approach the steady state would be more than six times longer, that is, more than 30 years instead of 5 years in the actual fishery. This suggests that consumer preferences for a healthy stock status play an important role in stabilizing the fishery under restricted open access.

Contrasting fishery dynamics with and without consumer preferences for stock sustainability under optimal fishery management, we next contrast the fishery dynamics of the Western Baltic cod fishery for optimal fishery management. Optimal fishery management, thereby, is defined as fishing that maximizes the net present value of economic surplus from the fishery, Equation (10). We use a social discount rate of 2% per year. Again, we summarize the results in a phase diagram, shown in Figure 6, plotting catches and fish population growth as functions of spawning stock biomass.

As in Figure 2, the green curve shows the equilibrium yield of the fishery also in Figure 5 but now over a larger range of stock sizes. This shows that the unfished biomass for the Western Baltic cod population is estimated to be 270,000 tons. The dots again show the data from ICES (2022a,

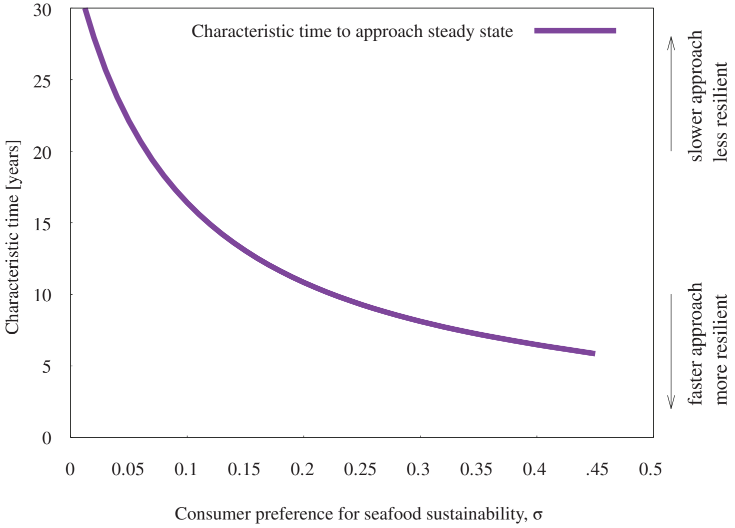


FIGURE 5 Resilience of the fishery in under restricted open access, as measured by the characteristic time at which the fishery approaches the steady state (Pimm, 1984).

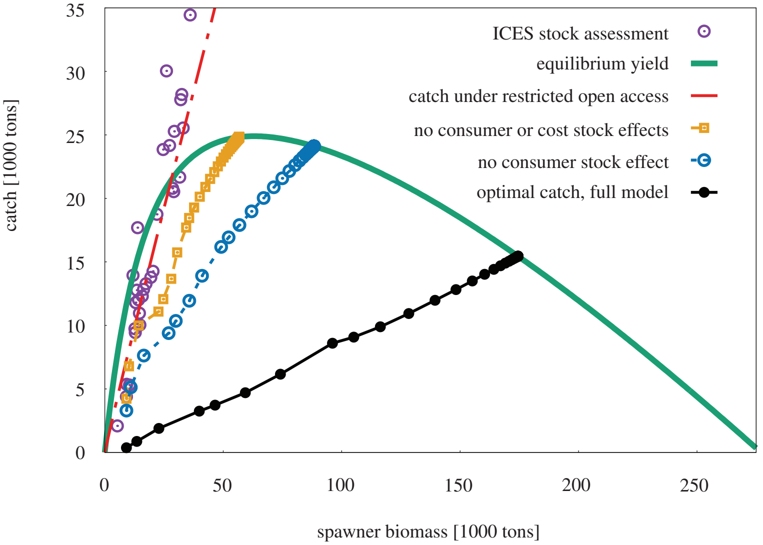


FIGURE 6 Phase diagram summarizing the dynamics of the Western Baltic cod fishery under restricted open access and under economically optimal management. The green curve shows the equilibrium yield of the fishery derived from the age-structured fish population model with fixed age-specific catchabilities. The dots show data from ICES (2022a, 2022b) stock assessment. The red curve shows the catch under restricted open access as simulated from the full bioeconomic model. The other curves show the outcome of dynamic optimization starting from the actual fish population in 2021 for three scenarios, namely the full model (black curve), only cost-based stock effect (i.e., setting $\sigma = 0$, blue curve), and no stock effect (i.e., setting $\sigma = 0$ and assuming a constant stock biomass in the cost function 3, yellow curve).

2022b) stock assessment, and the red curve shows the catch under restricted open access, as simulated from the full bioeconomic model.

The three other curves show results of dynamic optimization starting from the actual fish population in 2021 for three scenarios. The full model includes both a cost-based stock effect—as fishing costs (3) decrease with stock size—and the consumer stock effect. This is contrasted with a model where we hypothetically switch off the consumer stock effect, by setting $\sigma = 0$, and a third one where we also switch off the usual cost-based stock effect, additionally replacing B_t in the cost function (3) by a constant.

In this latter model, the steady state is close to the maximum sustainable yield, as could be expected for the relatively low social discount rate of 2% per year. The cost-based stock effect shifts the steady state to a stock size larger than the one that would deliver the maximum sustainable yield. This reduces the fishing costs but at the expense of a slightly reduced equilibrium yield. This model without consumer stock effect closely resembles the standard bioeconomic model where the stock effect comes from harvesting costs only (Clark & Munro, 1975; Grafton et al., 2007).

The full model that also includes the consumer stock effect leads to a harvest that is much lower, at any given stock size, than optimal harvesting in the standard model that does not exhibit a consumer stock effect. The reason is that a higher stock size would strongly increase the fish price and thus the economic benefit derived from the fishery. This warrants a strong sacrifice of yield, because catch from the more sustainable fishery is much more valuable for the consumers.

To further analyze the dynamics of the fishery under economically optimal management in the different scenarios, Figure 7 shows the development of spawning stock biomass (panel a), Simpson diversity of the fish population age structure (panel b), cod catch (panel c), and economic surplus (panel d) as functions of time. The full model results in a faster and more pronounced rebuilding of the stock (Figure 7a). Including the consumer stock effect results in lower catches over the complete time path as compared to ignoring this effect (Figure 7c). Economic surplus shows the interesting pattern that it is lower in the full model for the first three years, as rebuilding of the stock has priority in the beginning of the simulation (Figure 7d). Starting from 2025 onward, the positive outcomes

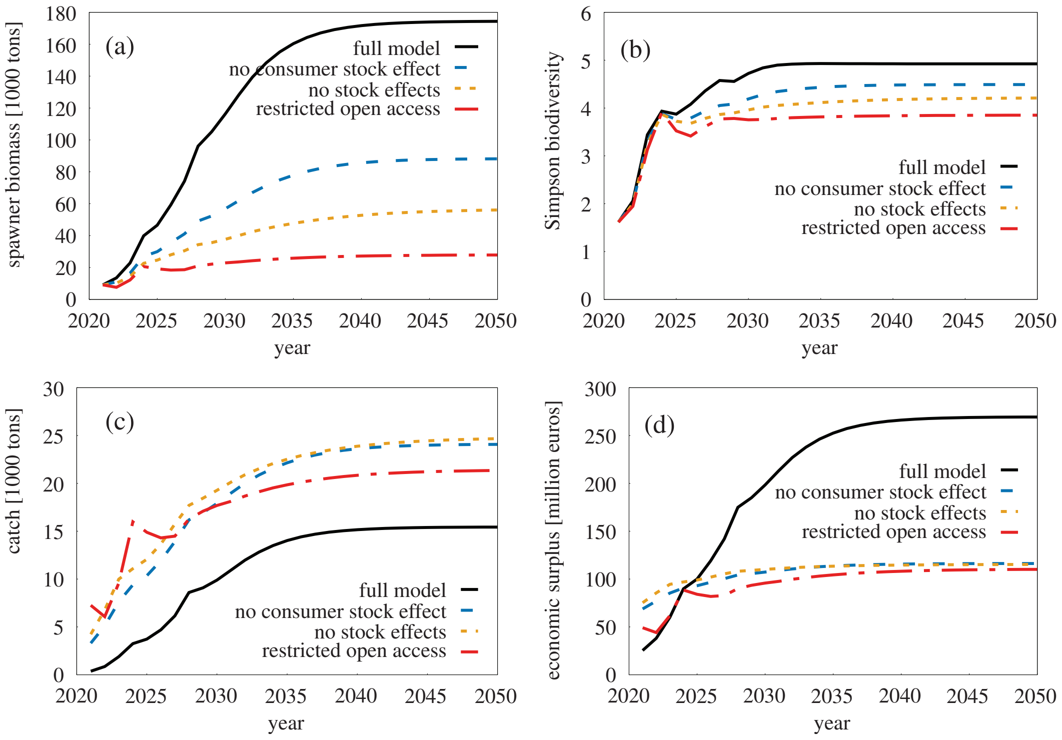


FIGURE 7 Time path of spawning stock biomass (a), Simpson biodiversity index (b), catch (c), and economic surplus (d) for different model configurations.

in terms of stock size, economic surplus as well as biodiversity (Figure 7c) start to materialize. Under full optimization, economic surplus is lower than in any of the other scenarios for a stock rebuilding phase of approximately 3 to 4 years, and higher only thereafter. Overcoming such a transition phase may be a challenge for fisheries policy. Yet, in present value terms, welfare is more than doubled if management would follow the fully optimal path.

5.3 | Effects on the age structure of the fish population

We conclude the analysis by studying the effect of the different model scenarios on the age structure of the fish population. Figure 7 shows that, after a transition period of about 5 years, the age structure of the fish population under economically optimal management with consumer preferences for stock sustainability is substantially more diverse than in the other scenarios. This effect becomes particularly clearly visible in steady state. The results for the steady state are shown in Figure 8.

The restricted open-access fishery leads to a strongly truncated age structure, dominated by young and very small fish (Figure 8, panel a). Such a population structure is rather susceptible to environmental fluctuations (Barneche et al., 2018) and possibly detrimental effects of climate change (Möllmann et al., 2021). Optimal fishing would lead to a more balanced age structure, even when ignoring consumer preferences for stock sustainability (Figure 8, panel b). Including that preference would lead to an age structure of the fish population where the largest and oldest age class contributes a substantial fraction to the overall stock (Figure 8, panel c).

5.4 | Sensitivity analysis

As the main contribution of the present paper is to quantify the magnitude of the consumer stock effect for fisheries outcomes, it is important to get an impression of the uncertainty of the quantitative results. One relevant uncertainty concerns biological fish population dynamics, which arises in particular due to the effects of climate change (Möllmann et al., 2021; Voss et al., 2019). This uncertainty has been studied elsewhere and is not of particular interest for the research question of this paper. We thus rather focus on the uncertainty in the economic part of the model.

Specifically, the aim is to assess the sensitivity of results with respect to the elasticities of the demand and cost function that are related to the consumer stock effect, and the ordinary stock effect on fishing costs. Thus, we are interested in the uncertainty of the stock elasticity of demand, σ; the price flexibility, η; and the elasticity of marginal harvesting costs, ε. To assess the parameter uncertainty with respect to these elasticities, we present results from a Monte Carlo sensitivity analysis, based on 1000 randomly drawn parameter sets from normal distributions with means given by the

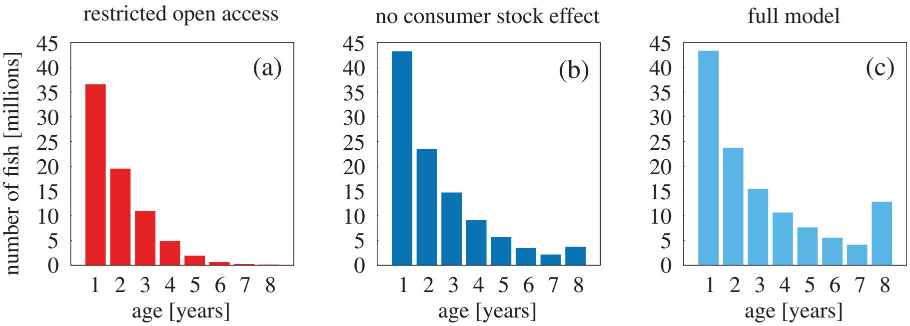


FIGURE 8 Age structure of the steady-state fish population in three model scenarios.

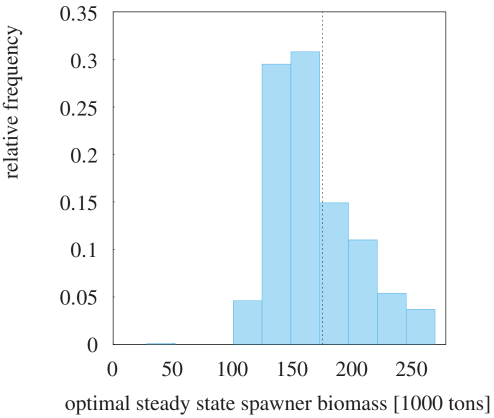


FIGURE 9 Histogram showing the results of a Monte-Carlo sensitivity analysis with respect to parameter uncertainty in the elasticities relevant for the stock effect: the stock elasticity of demand, price flexibility, and elasticity of marginal harvesting cost. The graph shows the relative frequency of spawner biomass in optimal steady state in 10 bins. The result for the standard parameter set is an optimal steady state stock size of 174,400 tons, shown as dashed line.

estimates reported in Tables 2 and 3, and standard deviations given by the respective standard errors. For each of these parameter sets, we computed the optimal steady state. Figure 9 shows the histogram (with 10 bins) of the resulting values for the optimal spawner biomass. This analysis reveals a considerable uncertainty of results: The standard deviation is 33,400 tons, about 19% of the optimal steady state stock size for the standard parameter set, which is 174,400 tons. Thereby, the distribution of possible optimal steady state stock sizes is skewed: The difference between the upper bound of the confidence interval (about 256,000 tons) to the mean result is larger than the difference between the mean result and the lower bound of the confidence interval (about 112,000 tons).

Another relevant parameter is the discount rate, which we have set to $\delta = 2\%$ per year in the reference parameter set. Varying the discount rate, we find an almost linear decline of the optimal steady state stock size with the discount rate: The optimal steady state spawning stock is 182,000 tons for an interest rate of zero and 150,000 tons for an interest rate of 10% per year.

6 | DISCUSSION AND CONCLUSION

We have developed a model that seamlessly integrates consumer preferences for stock sustainability estimated from a choice experiment with an empirical age-structured bioeconomic fishery model. We have applied this model to the case of the Western Baltic cod fishery and derived insights into how consumer preferences for sustainably sourced seafood changes fishery dynamics under (restricted) open access and under economically optimal management.

We found that a "consumer stock effect" arises, which stabilizes a fishery under open access and which decreases catches under economically efficient management. For the case of the Western Baltic cod fishery, and considering the preferences of German fish consumers, we find that these effects are of large magnitude. Switching off the consumer preferences for stock sustainability, the characteristic time to approach the restricted open access steady state would be more than six times longer than for the actual fishery where consumers care about the sustainability of the stock that provides the fish. Switching off the effect that the price would decrease when the stock is overfished would lead to much higher catches at low stock sizes, possibly leading to a fast collapse of the resource stock. We conclude that the consumer preference for sustainably sourced seafood has the important effect that it enhances the resilience of the poorly managed fishery.

Considering the case of economically optimal management, we found that the consumer stock effect strongly reduces optimal catches to less than half the amount that a standard model without consumer stock effect would imply for the particular fishery studied here. Accordingly, the optimal steady state for the Western Baltic cod fishery is much higher than the stock that would deliver the maximum sustainable yield. This would also benefit biodiversity, as it would lead to a more favorable age structure of the fish population, with older individuals more abundant than at present. This, in turn, could also contribute to the resilience of the stock against environmental fluctuations (Barneche et al., 2018). We conclude that economically optimal fisheries management, which adequately takes into account consumer preferences for sustainably sourced seafood, should be more conservative than implied by purely biological models.

In case of the Western Baltic cod fishery, management is moving toward ecosystem-based fisheries management (EBFM), and scientific advice increasingly takes into account economic considerations. Our study suggests that this should also consider more thoroughly the consumer preferences for sustainably sourced fish products. It also contributes to the evidence that management of the Western Baltic should set total allowable catches at much more conservative levels than previously and that the key challenge remains to reduce the fishing mortality to sustainable levels, which would eventually allow for a rebuilding of the stock. According to our model, the transition dynamics take 3 to 4 years until economic surplus, including the consumer stock effect, outperforms the alternatives. During this period with low catches and profits, bridging solutions for the fishery need to be found.

The demand function in our model has the usual downward-sloping property: The price that consumers are willing to pay for a kilogram of fish is decreasing with the overall quantity on the market. Dao et al. (2023) show that this effect tends to go in the opposite direction as the "consumer stock effect," which is the focus of the present paper: Generally, catches increase with stock size, but this effect is attenuated if the price flexibility is high. Accordingly, a high price flexibility decreases the resilience of the fishery under open access (Dao et al., 2023). We would expect price flexibility to be high if the fish is primarily sold on a local market or if few substitutes are available for the fish under consideration. In such situations, the consideration of the consumer stock effect may be even more important.

Naturally, our analysis comes with a number of limitations. One is that the discrete choice experiment is a stated preference method, which always comes with the question about the external validity of results. We are confident that consumers actually do care for the status of the fish stock, as this is confirmed by revealed preference studies (Asche et al., 2015). The exact magnitude of the effect may be over- or underestimated, though. Moreover, our model uses a particular specification of the demand function, in this case an iso-elastic specification. This means that we assume consumers are always willing to pay more if the stock is higher—even if the stock is well within safe biological limits. This means that the quantitative results, especially on optimal management at larger stock sizes, should not be taken too literally. Also, we have ignored that consumers have a preference for larger fish (Quaas et al., 2013; Zimmermann & Heino, 2013), which may have similar effects as the consumer preferences for stock sustainability (Zimmermann et al., 2011a). A similar uncertainty applies to the biological part of the model. Climate change is imposing a serious threat to the cod populations in the Baltic Sea. Optimal management would have to respond to climate change (Voss et al., 2019; Voss et al., 2021). Although this does not qualitatively change our conclusions about the effect of a consumer preferences for stock sustainability, the quantitative results for the Western Baltic cod fishery will likely have to be adjusted in the future due to climate change effects.

Also in terms of consumer preferences, the Western Baltic cod fishery has some special characteristics: German households are perhaps more environmentally conscious than others. Therefore, the quantitative results might not be representative for other fisheries. Yet, a recent review found a willingness to pay for sustainable food also for Africa, America, Asia, and Europe outside Germany (Cecchini et al., 2018), indicating that similar effects can be expected for other fisheries as well.

In sum, we conclude that fishery management should take the consumer preferences for sustainably sourced seafood seriously and accordingly set fishing quotas more conservatively to generate the extra value associated with sustainably sourced seafood.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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