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Analysis

# Fishing industry borrows from natural capital at high shadow interest rates[☆]

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ABSTRACT

Fish stocks can be considered as natural capital stocks providing harvestable fish. Fishing at low stock sizes means borrowing from the natural asset. While fishing a particular quantity generates immediate profits and income, an interest rate has to be paid in terms of foregone future fishing income, as the fish stock's reproductive capacity remains low and fishing costs stay high. In this paper we propose to apply the concept of shadow interest rate to quantify the degree of overfishing. It incorporates the relevant biological and economic information and compares across fish stocks. We calculate the shadow interest rates for 13 major European fish stocks and find these rates to range from 10% to more than 200%. The concept of the shadow interest rate can be used to make the economic consequences of overfishing transparent and to evaluate the profitability of short-term catch reductions as investments in natural capital stocks.



## 1. Introduction

"We borrow the earth from our children," environmentalists say—but at what rate of interest? The 2002 World Summit on Sustainable Development (Johannesburg) made it imperative to manage fish stocks in a sustainable way, but globally the number of fish stocks subject to overfishing is still increasing (FAO, 2011; Pauly and Froese, 2012). Even in developed regions like Europe, many commercial fish stocks have sunk far below levels that can produce maximum sustainable yields ($B_{MSY}$, Froese and Proelss, 2010, 2012). From an economic point of view, fish stocks can be considered natural assets or capital stocks providing harvestable fish. But with stock sizes relatively low, going on fishing means borrowing from the natural capital stock, since reduced fish stocks grow more slowly, which in its turn make future catches smaller and increases fishing costs. Accordingly, the immediate profits and income thus obtained are offset by an interest rate in terms of foregone future fishing income, as the fish stock's reproductive capacity remains low and fishing costs stay high. According to standard resource economics, a species' optimal stock size is determined by equating the so-called "own rate of interest" to the market interest rate at which a fisherman can borrow (or invest) money from (or at) a bank (Clark, 2010; Clark and Munro, 1975). This optimality rule, however, provides little information about the extent to which the actual stock size differs from optimal, or the degree to which current stocks are overfished. For single fisheries, the usual gages of overfishing either indicate the discrepancies between current biomass or current fishing mortalities and reference points like maximum sustainable yield biomass (BMSY) or the constant fishing mortality ($F_{MSY}$) associated with MSY (Beddington et al., 2007), or they compare the net present values of resource rents under current and optimal management (e.g. World Bank, 2008). These biological and economic approaches differ with respect to their objectives, but what they have in common is that they set target reference points for the fishery (for example, maximum sustainable yield, MSY, or maximum economic yield, MEY). Often, however, they provide little guidance on how to reach these target levels, i.e., how to manage the transition from the current state to the target state.

As an alternative way of quantifying the degree of overfishing and its economic costs, we propose using the concept of shadow interest rate (SIR). The SIR refers to the *current* actual catch (under regulation: the actual total allowable catch, TAC) and thus indicates how to adjust current fishery policies. As the SIR can be compared across fish stocks, it also indicates the stock for which stock implementing improved management rules is most profitable. Technically speaking, the SIR is the counterfactual interest rate (or discount rate) at which the actual

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catch (or TAC) in the base year would have been economically efficient. Intuitively, it expresses the interest rate that fishermen have to pay when they continue fishing at low stock sizes instead of letting the stock grow to a more productive level. In doing so, they forgo future income and act as if they were borrowing money for consumption today that has to be paid back at a later date. If a fisherman borrows money from a bank, the future burden will depend on the level of the market interest rate. In the same vein, the opportunity costs of high current catches increase with the SIR.

Note that the SIR can be compared to both market interest rates (if one is interested in the economic profitability of fisheries) and to social discount rates (if one is interested in the total economic benefits and costs of fishery policies). Fishing is only economically profitable and social benefits are only higher than social opportunity costs up to the catch volume at which the SIR equals the market interest rate and the social discount rate, respectively. If the harvest exceeds the optimal quantity, the SIR reveals the actual degree of overfishing and indicates the true economic costs of borrowing from the natural capital stock. In other words, the SIR expresses the interest rate at which fishermen "borrow the fish from their children."

In this paper we estimate the shadow interest rates for 13 major fish stocks managed by the European Union (ICES, 2010a). We focus on European stocks, because all of them are regulated by total allowable catches set according to the European Common Fisheries Policy. For this estimate, we need to combine biological information on the population dynamics of fish and economic information on harvesting costs. To parameterize the population models, we use data from stock assessments published by the International Council for the Exploration of the Seas (ICES, 2010a, 2011a). We estimate the harvest cost functions on the basis of the observed behavior displayed by fishermen operating under *de facto* open-access conditions. The calculations further require assumptions about future management, i.e. in the period after the first year of harvesting. For this purpose, we consider two different scenarios of future management regimes: a) economically efficient management, and b) $F_{\mathrm{MSY}}$ management. Economically efficient management means that for a given interest (or discount) rate the trade-off between current and future fishing income is solved efficiently at each point in time (a formal definition is given in Appendix A4). $F_{\mathrm{MSY}}$ management, by contrast, fixes fishing mortality ($F$) at a level that leads to maximal sustainable yield (MSY).

We find that SIRs vary between 16% (Norway pout) and 220% (North Sea saithe) under efficient management and between 10% (Norway pout) and 93% (North Sea saithe) under $F_{\mathrm{MSY}}$ management. Except for North Sea herring, SIRs are always higher under future efficient management than under $F_{\mathrm{MSY}}$ management, reflecting the fact that an investment in the natural capital stock typically yields a higher return under the former kind of management. These high SIR values contrast with market interest rates or social discount rates in northern European countries with exclusive economic zones in the North Sea and Baltic Sea, both of which are unlikely to exceed 6%, say (see Section 2). Against this background, we propose to use the shadow interest rates to evaluate fishery management and to quantify the economic costs of going on overfishing.

## 2. Models, Data, and the Concept of Shadow Interest Rate

### 2.1. Population Dynamics, Harvesting, and Profits

To describe the population dynamics under fishing pressure, we draw upon the canonical discrete-time model of resource economics (Clark, 2010; Spence, 1974). The total stock biomass $B_t$ at time $t$ is governed by the growth equation

$$B_{t+1}-(B_t-H_t)=r_{\max}(B_t-H_t)\left(1-\frac{B_t-H_t}{B_{\max}}\right)+u_t, \tag{1}$$

where $H_t$ is total harvest in year $t$, $r_{\max}$ is the intrinsic growth rate, $B_{\max}$ is equilibrium stock in the absence of harvest, and $u_t$ is a mean zero-residual process. We estimate $r_{\max}$ as a co-integrating parameter by means of a reduced rank regression (Johansen, 1991) conditional on an a priori choice of $B_{\max}$. For details, see Appendix A2. The data we use are the most recent stock assessments from the ICES for European fish stocks. The resulting estimates for $r_{\max}$ (with standard error) and $B_{\max}$ are given in Table A1. According to Eq. (1), the constant instantaneous fishing mortality ($F_{\mathrm{MSY}}$) associated with MSY can be calculated from our estimates of $r_{\max}$ as $F_{\mathrm{MSY}}^{\mathrm{est}}=\log(1+0.5r_{\max})$. This figure can be compared to $F_{\mathrm{MSY}}$ estimates from ICES. Such estimates are available for Eastern Baltic cod ($F_{\mathrm{MSY}}^{\mathrm{est}}=0.31$ vs. $F_{\mathrm{MSY}}=0.3$ according to ICES), North Sea herring ($F_{\mathrm{MSY}}^{\mathrm{est}}=0.21$ vs. $F_{\mathrm{MSY}}=0.25$ according to ICES), Irish Sea herring ($F_{\mathrm{MSY}}^{\mathrm{est}}=0.13$ vs. $F_{\mathrm{MSY}}=0.19$ according to ICES), North Sea plaice ($F_{\mathrm{MSY}}^{\mathrm{est}}=0.30$, identical to $F_{\mathrm{MSY}}=0.3$ according to ICES), and North Sea saithe ($F_{\mathrm{MSY}}^{\mathrm{est}}=0.30$, identical to $F_{\mathrm{MSY}}=0.3$ according to ICES). Overall, the figures estimated here tend to be slightly lower than ICES estimates.

For comparison, and to illustrate the fact that the SIR concept can be applied more generally, we use an alternative age-cohort model (Tahvonen, 2009) with eight age classes and apply it to the Eastern Baltic cod fishery. The details of the age-cohort model can be found in Appendix A5.

Total economic benefits $\pi(H_t, B_t)$ derived from fisheries mean welfare for consumers of fish, producers (i.e. fishermen), and workers in the fishing industry (Copes, 1972; Stoeven and Quaas, 2012; Turvey, 1964). In addition, there may be non-market costs or benefits of fisheries, for example when the stock of a fish species has a non-use value (Bulte et al., 1998; van Kooten and Bulte, 2000). Using total economic benefits to derive the SIR is particularly relevant if one wants to assess fishery policies by comparing the SIR to the social discount rate. Here we focus on the economic profitability of fisheries. We therefore assume that demand for each fish stock under consideration is perfectly elastic at price $p$, so that consumer welfare does not depend on the catches from a particular stock (Quaas and Requate, forthcoming). Furthermore, we assume that the wage rate is independent of employment in the respective fisheries, so that workers' surplus does not depend on fishing effort. These assumptions seem fairly reasonable for the European fish stocks studied here. Landings from each of the fish stocks considered are small compared with the volume traded on the entire market, which is typically an international or even global market. Furthermore, employment in the northern European fishing industry is small compared to overall employment. Finally, we disregard non-market benefits, as no reliable data is available for the fish stocks considered here. Under these conditions, the economic benefits derived from fisheries consist only of the annual economic profit from fishing. Using the Clark-Spence model this is given by

$$\pi(H_t,B_t)=pH_t-CF_t=pH_t+C\ln\left(1-\frac{H_t}{B_t}\right), \tag{2}$$

where $C$ is a constant cost parameter and $p$ is the constant output price of fish. Following Spence (1974) and Clark (2010), the harvesting costs are assumed to be proportional to the constant instantaneous fishing mortality $F_t=-\ln(1-H_t/B_t)$ that gives rise to a total harvest $H_t$ in year $t$ when the initial stock size is $B_t$. Hence, instantaneous harvesting costs are inversely proportional to the current stock size, as in the Gordon-Schaefer model (which is formulated in continuous time). For schooling fish species, the Clark-Spence harvesting cost function used here may overestimate the sensitivity of harvesting costs to stock size. However, the Clark-Spence harvesting cost function is also commonly used in the literature for schooling species such as North Sea herring (Bjørndal and Conrad, 1987; Nostbakken, 2008; Nostbakken and Bjørndal, 2003).

Under open access, fishermen would increase harvest until marginal profits are zero, i.e. until $p-C/[B_t-H_t]=0$, or, by rearranging,

$$B_t-H_t=\frac{C}{p}\equiv c. \quad (3)$$

While parameter $C$ is measured in monetary units, we can use parameter $c\equiv C/p$ to measure the constant marginal costs of instantaneous fishing mortality in units of fish biomass. Thus for an open-access fishery, parameter $c$ can be estimated from the stock size that remains in the sea after fishing in year $t$, i.e. the stock biomass $B_t$ at the beginning of the fishing season minus the total harvest $H_t$. Clearly, condition (3) also applies to a regulated fishery when regulations are not binding, i.e. when regulations do not actually restrict catches. We refer to such a situation as *de facto* open access. From 1984 to 2008, several European fish stocks were harvested under what were *de facto* open-access conditions (e.g. Baltic cod, Kronbak, 2005).[1] The criterion for *de facto* open access that we apply in this study is that in at least three consecutive years between 1984 and 2008 the catch was less than 90% of the total allowable catch (TAC). We thus only include stocks for which TACs were set in this period and exclude those for which additional management measures (effort restrictions, area closures, or technical restrictions) had a restrictive effect on catches during the period 1984 to 2008 (according to ICES). Adopting a conservative approach, we use the minimum of observed cost parameters $c$ for the calculations. The resulting cost parameter values are indicated in Table A1. For two stocks in the table (North Sea cod and North Sea herring), this approach is not applicable, as the TACs were fished to capacity in all years. In these cases, we use cost parameter estimates from the literature (see Appendix A3).

### 2.2. The Shadow Interest Rate

We define the shadow interest rate of harvesting a quantity $H_t$ in a base year $t$ as the hypothetical constant interest rate $i$ according to which $H_t$ would be the dynamically efficient harvest in $t$, given a particular fixed management rule from year $t+1$ onwards. We describe this hypothetical future management by the harvest control rule $\hat{H}(B_t)$ determining harvest in year $t$ as a function of the fish stock $B_t$ in that year. We will consider two different harvest control rules: a) economically efficient management, and b) $F_{\text{MSY}}$ management. Efficient management (scenario a) means that the present value of profits from fishing at interest, or discount, rate $i$ is maximized when following that rule from year $t+1$ onwards (see Appendix A4). The resulting control rule requires harvesting nothing as long as the stock is below its optimal size and maintaining this optimal stock size at a sustainable level once reached (i.e. a most-rapid approach to the optimal steady state stock size, see Clark, 2010; Reed, 1979; Spence, 1974). By contrast, $F_{\text{MSY}}$ management (scenario b) fixes the fishing mortality to the value that leads to the maximum sustainable yield in the long run and translates into a harvest control rule $\hat{H}(B_t)=(1-\exp(-F_{\text{MSY}}))B_t$. This rule captures the essence of a recent proposal by the European Commissioner on Fisheries and Maritime Affairs (EC, 2011).

For either rule, the present value of fishing profits from $t+1$ onwards is given by

$$V=\sum_{\tau=t+1}^{\infty}\left(\frac{1}{1+i}\right)^{\tau-t}\pi\left(\hat{H}(B_\tau),B_\tau\right), \quad (4)$$

where the development of $B_\tau$ is given by (1) with the harvest control rule $\hat{H}(B_\tau)$.

[1] We only include such fish stocks in this analysis where we have clear indications of *de facto* open-access conditions in the period 1984 to 2008.

On this basis, we now define the shadow interest rate.

**Definition 1.** The shadow interest rate (SIR) corresponding to the $\text{TAC}_t$ in period t is defined as solution $i$ of the following equation:

$$\begin{aligned}\pi(\text{TAC}_t,B_t)&+\sum_{\tau=t+1}^{\infty}\left(\frac{1}{1+i}\right)^{\tau-t}\pi\left(\hat{H}(B_\tau),B_\tau\right)\\&=\max_{H_t}\left\{\pi(H_t,B_t)+\sum_{\tau=t+1}^{\infty}\left(\frac{1}{1+i}\right)^{\tau-t}\pi\left(\hat{H}(B_\tau),B_\tau\right)\right\}, \quad (5)\end{aligned}$$

where the evolution of $B_\tau$ for $\tau\geq t+1$ is given by (1) with the harvest control rule $\hat{H}(B_\tau)$.

The first term on both sides of Eq. (5) is the net economic benefit derived from the fishery in year $t$, while the second term is the present value of future profits (i.e. from year $t+1$ to infinity) at the interest (or discount) rate $i$. On the left-hand side of Eq. (5), the net economic benefit in year $t$ depends on the current TAC, while on the right-hand side of Eq. (5) the catch $H_t$ in year $t$ is chosen so as to maximize the present value of economic benefits from the fishery over the entire time horizon. The SIR is the counterfactual interest rate $i$ at which both sides of Eq. (5) are equal, i.e. at which $\text{TAC}_t$ and the optimal catch in year $t$ coincide.

Note that the SIR depends on harvest $\text{TAC}_t$ in base year $t$, as this determines $B_{t+1}$, the initial stock size in $t+1$. In Appendix A4 we show that an SIR always exists and is unique for economically efficient management. However, the SIR is finite only if the TAC in year $t$ is actually binding. Otherwise profits in year $t$ would be zero, which means that the investment costs of a marginal TAC reduction are zero as well. The corresponding SIR would be infinity. Note further that Definition 1 does not depend on the specific assumption that economic benefits from fishing are given by the fishing profits. The concept can also be applied to situations where consumer welfare and non-market benefits matter for decision-making.

The SIR is related to other well-known concepts used in cost-benefit analysis. First, it is related to the internal rate of return (IRR). The IRR of a project is the virtual constant annual interest rate at which the present value of future profits from the project is equal to the project's opportunity cost (Samuelson, 1937). The SIR is the IRR of the project that consists in marginally reducing the TAC below the reference level in period $t$. Second, the SIR is related to the concept of the (net) present value (PV). According to this concept, the current TAC should be set at the level that maximizes the PV of the fishery at a given interest rate. In Appendix A4 we show that this approach is equivalent to setting the TAC so that the corresponding SIR is equal to the market interest, or social discount, rate (assuming that economically efficient management will prevail in the future).

As discussed above, the SIR can be compared to both the market interest rate and to the social discount rate. Depending on the purpose and the fishery under study, different interest or discount rates have to be used. The market interest rate (on borrowed money) set by the European Central Bank in 2011 was 2% per year and has not exceeded 6% since 1999. As the development of fish stocks is subject to environmental uncertainty, it may be appropriate to include a risk premium in the interest rate. But even with such a risk premium, the current market interest rate relevant for fisheries management in northern Europe is unlikely to exceed 6%. Similarly, countries use different social discount rates. Relevant for our application are the social discount rates of the northern EU member states. For these countries, the European Commission (EC, 2008: 209) proposes social discount rates between 2.8% (for the Netherlands) and 5.3% (for Poland). Hence, the relevant social discount rate is also well below 6%. In the following we therefore use a conservative value of 6% for comparison with the SIR.

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**Table 1**
Shadow interest rates for 13 major European fish stocks. Shadow interest rates for the TAC in 2010, assuming economically efficient or $F_{MSY}$ management from 2011 onwards; standard deviations are given in brackets.

| Stock | Shadow interest rate, efficient management | Shadow interest rate, $F_{MSY}$ management |
|---|---|---|
| Cod, Eastern Baltic Sea | 66% (3%) | 40% (1%) |
| Cod, North Sea | 199% (24%) | 90% (7%) |
| Herring, Central Baltic Sea | 48% (7%) | 29% (3%) |
| Herring, North Sea | 19% (10%) | 21% (9%) |
| Herring, Irish Sea | 17% (1%) | 11% (1%) |
| Norway Pout, North Sea | 16% (2%) | 10% (1%) |
| Plaice, Western English Channel | 135% (22%) | 67% (9%) |
| Plaice, Irish Sea | 67% (8%) | 39% (4%) |
| Plaice, North Sea | 56% (3%) | 34% (2%) |
| Saithe, North Sea | 220% (64%) | 93% (21%) |
| Sole, Celtic Sea | 27% (4%) | 18% (2%) |
| Sole, Eastern English Channel | 34% (4%) | 24% (2%) |
| Sole, North Sea | 103% (14%) | 55% (6%) |

## 3. Results

The SIRs for the 13 European fish stocks included in our analysis are indicated in Table 1 for both future management scenarios. Standard deviations are computed by means of Monte-Carlo simulations. We use random samples of 1000 parameter sets for $r_{max}$ and $c$, assuming that the parameter values are independently normally distributed with means and standard deviations as shown in Table A1. For each parameter set, we compute the SIR and determine the standard deviation of the sample of SIRs thus obtained.

We see that according to the SIRs all stocks investigated are overfished (Table 1; Fig. 1). The figures vary between 16% (Norway pout) and 220% (North Sea saithe) under scenario a) and between 10% (Norway pout) and 93% (North Sea saithe) under scenario b). The SIRs are typically higher under future efficient management than under $F_{MSY}$ management, reflecting the fact that an investment in the natural capital stock typically yields a higher return under the former kind of management. SIRs, and with them the extent of economic overfishing, differ substantially across stocks. In our sample, Norway pout is least overfished with a SIR of about 10% per year under $F_{MSY}$ management.

To analyze how the SIR depends on harvest and stock size, we take a closer look at its evolution over time for a particular species. Our example is Eastern Baltic cod (ICES, 2011a), one of the most important European stocks (Dickson and Brander, 1993). Fig. 2 shows the evolution of Eastern Baltic cod's SIR over time, assuming that economically efficient management will prevail in future (scenario a). The upward-sloping, dashed lines represent iso-SIR lines in the harvest-stock size plane. Note that at any given stock size, a lower harvest level (moving "south") induces a lower SIR. This means that borrowing from natural capital becomes less expensive, the more restrictive the TAC is. The contour line for the current interest rate (assumed to be 6% per year) gives the economically efficient harvest rule. The contour line for a SIR of 0% represents the harvest rule according to Maximum Economic Yield (MEY) management. The contour line labeled "∞" and all points to the "north–west" of it indicate *de facto* open-access conditions. The solid lines show the evolution of the Eastern Baltic cod fishery. We observe that SIRs for Eastern Baltic cod varied substantially after 1966, exceeding 50% in most of the years. In the late 1970s and early 1980s, stock sizes were high and SIRs relatively low, at values between 10% and 25% per year. Slightly lower catches would have led to SIRs at reasonable economic levels. During the 1980s and early 1990s, SIRs increased dramatically, almost reaching open-access levels in the late 1990s and early 2000s. In recent years, the management of Eastern Baltic cod has substantially improved, as is reflected by the return to a continuously decreasing SIR. Similar patterns can be found for other stocks, e.g. North Sea herring.

For Eastern Baltic cod in 2010, we further calculate the SIR for varying hypothetical TACs, when the stock biomass was 333,000 tons and the actual TAC 51,270 tons. The results are shown in Fig. 3. The solid lines show the SIRs for economically efficient management, the dashed lines for $F_{MSY}$ management from 2011 onwards. We show results for both the Clark–Spence model (black lines) and the age-cohort model (grey lines).

The SIRs derived from the two modeling approaches differ. With the actual TAC in 2010, the figures are 66% (standard deviation 2%) for the Clark–Spence model and 55% (standard deviation 14%) for the age-cohort model under economically efficient management. Under $F_{MSY}$ management the resulting figures are 37% (standard deviation 1%) for the Clark–Spence model and 54% (standard deviation 8%) for the age-cohort model. The standard deviations show that uncertainty about parameter values has a relatively strong effect on the results from the age-cohort model over and against the Clark–Spence model. Furthermore, the SIRs derived from the age-cohort model increase much more strongly with harvest than those derived from the Clark–

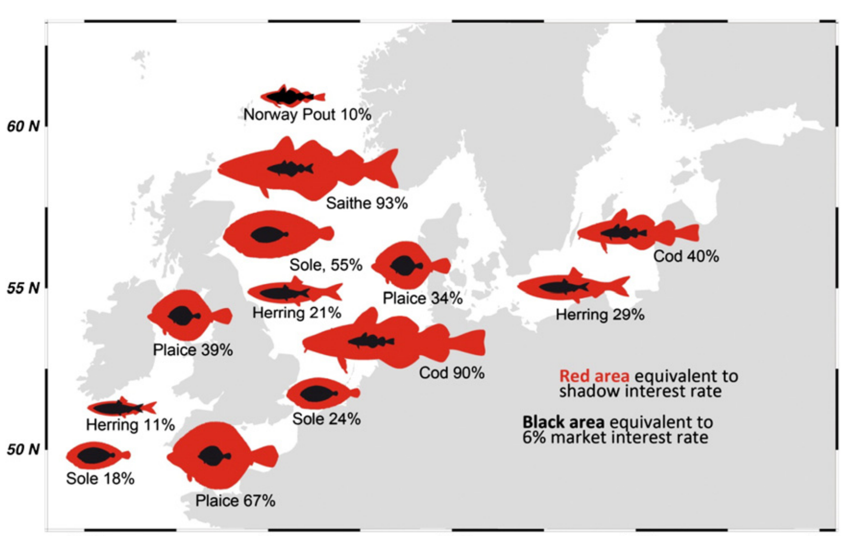


**Fig. 1.** Shadow interest rates for 13 major European fish stocks. Shadow interest rates (in % per year) for the 2010 TAC, assuming $F_{MSY}$ management from 2011 onwards.

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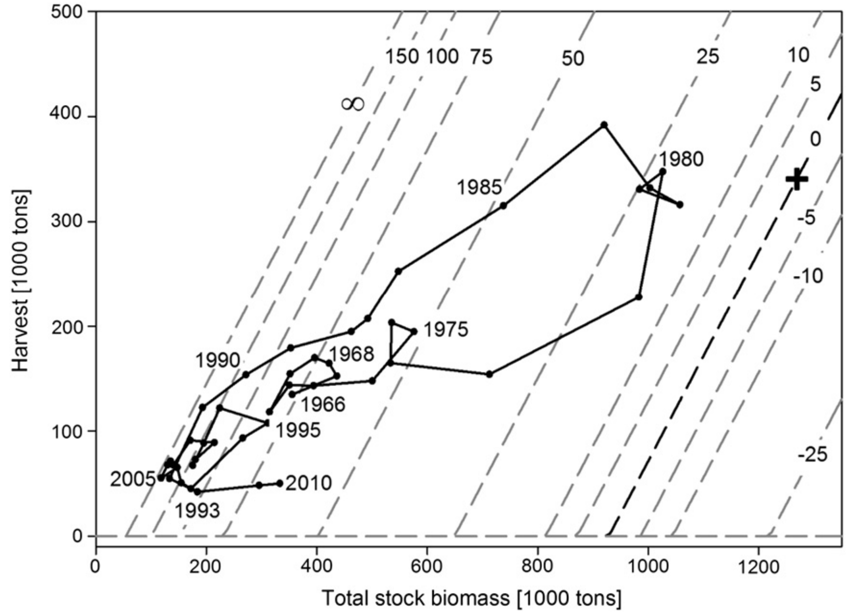


**Fig. 2.** Shadow interest rates for Eastern Baltic cod. Harvest and total stock biomass for Eastern Baltic cod from ICES (2011) data, with contour lines indicating SIRs (in % per year) for economically efficient management. The '+' marks the estimated maximum economic yield (MEY).

Spence model. The reason is that the age-cohort model captures the effects of fishing on the age structure of the stock. Relatively low catches can be obtained by harvesting the older age groups only. Harvesting high amounts at the given stock size is only possible when many young fish are caught as well. As this drastically reduces the number of individual fish in the stocks and hence fishing opportunities in future years, the SIR at which such a high TAC is borrowed from the natural capital stock strongly increases with harvest. In all cases, the SIR goes to infinity when the TAC approaches open-access harvest level. This is the harvest level at which current fishing profits are zero. Hence, opportunity costs of a marginal TAC reduction are zero, rendering such a costless investment infinitely profitable, as measured by the SIR.

## 4. Conclusions

We have introduced the shadow interest rate (SIR) concept to quantify the degree of overfishing imposed by a specific quantity of catch at a given stock size. This quantity can be determined by a total allowable catch (TAC) regulation or some other form of regulating the fishery. The SIR can be interpreted straightforwardly as the

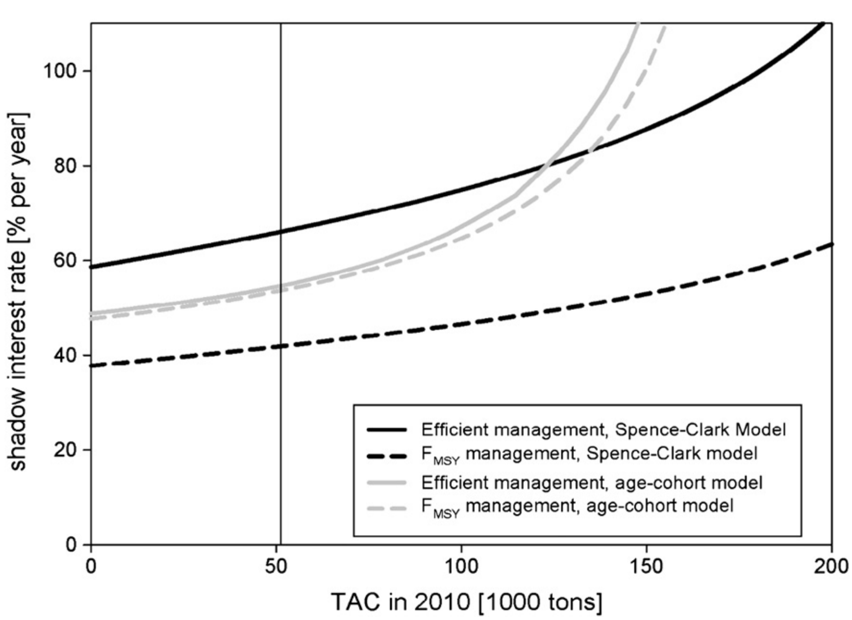


**Fig. 3.** Shadow interest rates (in % per year) for different hypothetical TACs for Eastern Baltic cod in 2010, when the stock biomass was 333,000 tons and the actual TAC 51,270 tons.

interest that has to be paid by fishermen in future years on the fishing income earned this year. It therefore also quantifies the economic return on reducing the catch to slightly below a value under discussion. Accordingly, such a catch reduction can be regarded as an investment in the natural capital stock, compared to the status quo. Our analysis of 13 major European fish stocks has shown that catch (in this case, TAC) reductions earn considerable interest. Recent management improvements have realized a part of these economic returns, for example in the Eastern Baltic cod or North Sea herring fisheries, where SIRs have decreased in recent years.

The shadow interest rate provides a universal measure for overfishing and can also be employed when several stock variables or several interacting species are under consideration. We have illustrated this by employing not only the standard Clark–Spence model but also a more sophisticated age-cohort model with a fish-population model containing many stock variables.

Moreover, the concept of SIR can be used to define a management target by setting harvest quantities (e.g. those implemented by TACs) so that SIRs just equal the interest rate, or social discount rate. For most of the fisheries studied here, this does in fact imply that fishing should be discontinued for a transition period devoted to stock rebuilding. Fishery regulators, such as the European Council of Fishery Ministers, have circumvented full closures of fisheries in the past. Justifications for continued fishing—if given at all—include maintaining employment or current income for fishermen. The SIR reflects the actual economic costs of doing so and indicates at what *de facto* interest rate continued fishing will result in borrowing present profits and income from the natural capital stock.

## Appendix A

**Table A1**

Estimated parameter values (standard errors in parentheses), stock biomass, and TAC in 2010 (2009 for the stock marked #) for 13 European fish stocks. $B_{max}$, $c$, $B_{2010}$, and $TAC_{2010}$ are all measured in 1000 metric tons. The second column gives the $r_{max}$ estimates obtained by means of the reduced rank regression with corresponding $B_{max}$ values in the third column; the fourth column gives the estimates by means of an OLS regression; and the fifth column gives the Dickey Fuller statistics (see Appendix B). Cost parameters for the stocks marked * are taken from the literature (see Appendix C).

| Stock | $r_{max}$ | $B_{max}$ | $r_{max}$(OLS) | DF | $c$ | $B_{2010}$ | $TAC_{2010}$ |
|---|---|---|---|---|---|---|---|
| Cod, Eastern Baltic Sea | 0.74 (.01) | 1875 | 0.72 (.04) | −5.665 | 55.2 (10.5) | 333.15 | 51.27 |
| Cod, North Sea | 0.66 (.01) | 4326 | 0.61 (.04) | −8.417 | 106.3 (10.2)* | 187.96 | 33.55 |
| Herring, Central Baltic | 0.28 (.04) | 4667 | 0.22 (.03) | −4.670 | 394.0 (57.1) | 828.21 | 126.37 |
| Herring, North Sea | 0.47 (.07) | 4703 | 0.51 (.05) | −4.675 | 1686 (712)* | 2860.00 | 164.30 |
| Herring, Irish Sea | 0.28 (.01) | 516 | 0.23 (.06) | −11.79 | 40.5 (8.6) | 168.14 | 10.15 |
| Norway Pout, North Sea | 0.31 (.04) | 2391 | 0.20 (.10) | −5.301 | 196.8 (59.9) | 983.72 | 162.00 |
| Plaice, Western Engl. Ch. | 0.69 (.04) | 13 | 0.67 (.08) | −5.471 | 2.4 (0.3) | 7.72 | 4.27 |
| Plaice, Irish Sea | 0.70 (.09) | 30 | 0.62 (.07) | −3.601 | 3.6 (0.5) | 9.65# | 1.43# |
| Plaice, North Sea | 0.70 (.05) | 1942 | 0.71 (.03) | −3.626 | 177.8 (7.6) | 580.45 | 63.82 |
| Saithe, North Sea | 0.69 (.06) | 1095 | 0.68 (.05) | −4.484 | 151.1 (38.3) | 302.98 | 107.04 |
| Sole, Celtic Sea | 0.44 (.03) | 11 | 0.41 (.04) | −6.583 | 1.9 (0.4) | 5.49 | 0.99 |
| Sole, Eastern English Ch. | 0.55 (.02) | 42 | 0.57 (.05) | −6.564 | 8.1 (1.1) | 21.34 | 4.20 |
| Sole, North Sea | 0.74 (.03) | 150 | 0.71 (.06) | −9.553 | 24.6 (3.8) | 55.30 | 14.10 |

## Appendix B. Estimation of model parameters

With regard to the stochastic features of the right- and left-hand-side variables in Eq. (1), it turns out that the majority of these time series are driven by highly persistent stochastic trends. In such cases, the estimation of $r_{max}$ from Eq. (1) by means of ordinary least squares (OLS) estimators faces the risk of spurious regressions, i.e. the significance of parameter estimates is merely a statistical artifact rather than an indication of a viable link among the variables subjected to regression. Under common stochastic trends characterizing both variables in Eq. (1), $r_{max}$ is a long-term co-integrating parameter that can be efficiently estimated by means of reduced rank regression techniques (Johansen, 1991). In the case of a common stochastic trend, the OLS estimator is known to be consistent but may suffer from small sample biases. If the time series in Eq. (1) show only transitory dynamic patterns, $r_{max}$ can be estimated efficiently by means of OLS. For both cases (common trends or transitory dynamics), covariance stationarity of the residuals $u_t$ indicates that the regression model is well balanced with regard to the time series processes involved.

For the implementation of the regression model, one has to rely on some a-priori choice of the initialization $B_{max}$. We consider a wide range of reasonable settings (95% confidence intervals of $B_{max}$ from Froese and Proelss, 2010). Then we optimize the quasi-log likelihood of a bivariate vector (autoregressive) representation of the variables in Eq. (1) over the considered support of $B_{max}$. Conditional on the selected value of $B_{max}$, $r_{max}$ is estimated by means of reduced rank regression and OLS.

Having only short time spans of time-series data at our disposal (for the set of 13 considered species the number of available observations is between 27 and 53), we refrain from providing detailed results on the prevalence of stochastic trends governing the variables in Eq. (1). Rather, we diagnose covariance stationarity of OLS residuals obtained from Eq. (1) by means of a Dickey Fuller test (Dickey and Fuller, 1979) and provide evidence on the differential between the reduced rank regression and OLS estimator of $r_{max}$. Table A1 documents these model diagnostics. According to Dickey Fuller statistics, estimated residuals from Eq. (1) are confirmed to be covariance stationary at common significance levels. With a critical value of $-3.365$ (MacKinnon, 1994), we can rule out the prevalence of a stochastic trend remaining in estimates of $u_t$ for all considered fish stocks with 5% significance (cf. fifth column in Table A1). Thus, the reduced rank and OLS estimator approximate $r_{max}$ consistently, with the former being efficient under common stochastic trends. Almost uniformly, OLS-based standard errors exceed their reduced-rank counterparts. Both estimators are numerically similar to each other. For all but three species (Sole Celtic Sea, Sole Eastern English Channel, Sole North Sea), the reduced rank estimator is within $\pm 2$ standard error bounds around its OLS counterpart. Using efficient reduced-rank regression, we thus can reduce the uncertainty in resulting values for the SIR. Moreover, both the consideration of deterministic time-series features and more general autocorrelation patterns neither improve the vector model characteristics at an overall level, nor do they deliver very different estimates for $r_{max}$.

## Appendix C. Cost parameter values from the literature and published data

### C.1. Baltic Sea cod

For a harvesting function of the type $H_t = B_t(1-\exp(-\eta E_t))$, a catchability coefficient of $\eta = 4.8\cdot 10^{-6}$ per day at sea was estimated by Kronbak (2005), using spawning stock biomass in the harvesting function. Re-estimating the catchability coefficient with total stock biomass, we obtain an estimate $\eta = 3.5\cdot 10^{-6}(0.9\cdot 10^{-6})$ per day at sea. Using Danish data for 1995–1999 (Kronbak, 2005) and new data from the same sources up to 2007, the average cost per day at sea/price ratio is 0.55 (0.085) tons/day at sea. This yields a cost parameter $\tilde{c} = 157$ (65). The point estimate in Kronbak (2005) is higher than our estimate $c = 55.2$ (10.5), but both have relatively large standard errors. As Kronbak (2005) uses accounting data, she derives the *average* cost parameter, while our method finds the cost parameter that applies to the *marginal* variable fishing costs. As the average costs may contain some quasi-fixed costs, it is plausible that our point estimate should be below that found in Kronbak (2005).

### C.2. North Sea herring

For a harvesting function of the type $H_t = B_t(1-\exp(-\eta E_t))$, a catchability coefficient of $\eta = 0.0011$ was estimated per vessel-year (Bjørndal and Conrad, 1987; Nostbakken, 2008). Spawning stock biomass was used in the harvesting function (Nostbakken and Bjørndal, 2003). Re-estimating the catchability coefficient with total stock biomass, we obtain an estimate $\eta = 0.00038(0.00009)$ per vessel-year. Variable cost per vessel-year/price ratios for 1998 to 2001 has been reported (Nostbakken, 2008; Nostbakken and Bjørndal, 2003). The average cost per vessel-year/price ratio is 640 (117) tons/vessel-year. This yields a cost parameter $\tilde{c} = 1686$ (712).

### C.3. North Sea cod

For North Sea cod, no published value for the cost parameter is available yet. To estimate a cost parameter, we use the most recent data for 2003–2008 from the Scientific, Technical, and Economic Committee for Fisheries (STECF, 2010). We use data on variable profits, value of landings, fishing and non-fishing income for the United Kingdom demersal trawl and demersal seiner fleet (vessels of more than 12 m length) and calculate profit and cost shares for cod according to the cod share in the value of landings. We estimate the fishing costs parameter for the whole North Sea cod fishery by dividing the resulting parameter by the United Kingdom's share in total landings as given by ICES (2011b).

## Appendix D. Economically optimal harvest control rule

We refer to economically efficient management if, for a given interest (or discount) rate, the trade-off between current and future benefits from fishing is solved efficiently at each point in time. This approach builds on capital theory (Clark and Munro, 1975), where the fish stock is considered to be one investment possibility, while other man-made or natural capital stocks are alternative investments. Dynamic efficiency then implies that the marginal return on investment (along the production possibility frontier) is the same for all alternative investments (e.g. Arrow and Kurz, 1970). Assuming that the marginal rates of return of the alternative investments do not depend on the size of the fish stock under consideration, we adopt a partial equilibrium approach, where the profitability of the alternative investments is captured by the given interest (or discount) rate $i$. Optimal management is found by maximizing the present value of profits

$$\max_{\{H_t,B_t\}} \sum_{\tau=t}^{\infty} (1+i)^{t-\tau}\pi(H_\tau,B_\tau). \tag{6}$$

subject to the population dynamics (1) with a given initial stock $B_t$. From the first-order conditions for optimal management, we obtain the following condition

$$1-c(B^\star-H^\star)^{-1} = \frac{1}{1+i}\left(1-c\left(B^\star-H^\star+r_{max}\left(B^\star-H^\star\right)\left(1-\frac{B^\star-H^\star}{B_{\max}}\right)\right)^{-1}\right) \times\left(1+r_{max}\left(1-2\frac{B^\star-H^\star}{B_{\max}}\right)\right) \tag{7}$$

This condition states that for the optimal stock size left in the sea after fishing (the "escapement") $S^\star = B^\star - H^\star$, current marginal profit from the last unit of fish harvested, given by the left-hand side of Eq. (7), equals the discounted marginal profits from an additional unit that escapes fishing, given by the right-hand side of Eq. (7). Condition (7) has a unique time-independent solution for the optimal escapement level $S^\star = B^\star - H^\star$. Note that this optimal escapement level depends on cost parameter $c$, market interest rate $i$, and the parameters governing the population growth, $r_{max}$ and $B_{\max}$. The economically optimal harvest control rule is then uniquely determined by $H(B_t) = \max\{B_t - S^\star, 0\}$ which describes the most rapid approach to the constant escapement level $S^\star$(Clark, 2010; Reed, 1979; Spence, 1974).

As for any given $i$ the solution to the optimization problem (6) exists and is unique, the SIR $i$ for harvesting a quantity $H_t$ at a stock size $B_t$ that solves Eq. (5) exists and is uniquely given by

$$i = -1+\left(1-c\left(B_t-H_t+r_{max}(B_t-H_t)\left(1-\frac{B_t-H_t}{B_{\max}}\right)\right)^{-1}\right) \times\frac{\left(1+r_{max}\left(1-2\frac{B_t-H_t}{B_{\max}}\right)\right)}{1-c(B_t-H_t)^{-1}} \tag{8}$$

It is straightforward to verify that the SIR as given by Eq. (8) is monotonically increasing in $H_t$. This implies that under economically efficient management in future, the current harvest quantity maximizing Eq. (6) at a given market interest rate is the same as the harvest quantity for which the SIR as given by Eq. (8) is equal to the market interest rate. In the case where the SIR is larger than the market interest rate for zero harvest as well, both approaches imply that nothing should be harvested at all.

## Appendix E. The age-cohort model

Following (Tahvonen, 2009) we set up an age-cohort model with 8 age classes according to the ICES standard assessments (ICES, 2010a, 2011a). The present value of fishing profits for a given interest rate $i$ is then given by

$$V = \sum_{t=0}^{T}\left(\frac{1}{1+i}\right)^t\left\{\sum_{s=1}^{8} p_s w_s(1-\exp(-F_t))q_s x_{st} - cF_t\right\}, \tag{9}$$

where $x_{st}$ are stock numbers of age $s$ in year $t$, $p_s$ are age-specific prices, $w_s$ age-specific weights, and $q_s$ age-specific relative catchabilities. Finally we use $F_t$ to denote the instantaneous fishing mortality in year $t$. The cost function is as in Spence (1974), where $c$ is the cost parameter in a similar way to the Clark-Spence model. Spawning stock biomass in year $t$ is given by $x_{0t} = \sum_{s=1}^{8} w_s\gamma_s x_{st}$, where $\gamma_s$ are the age-specific maturities. Population dynamics are described by

$$\begin{aligned} x_{1,t+1} &= \varphi_1(1-\exp(-\varphi_2 x_{0t}/\varphi_1)) \\ x_{s,t+1} &= \alpha_{s-1}(1-q_s(1-\exp(-F_t)))x_{s-1,t} \qquad \text{for } s=2,\dots,7 \\ x_{8,t+1} &= \alpha_7(1-q_7(1-\exp(-F_t)))x_{7t}+\alpha_8(1-q_8(1-\exp(-F_t)))x_{8t}. \end{aligned} \tag{10}$$

The number of recruits $x_{1,t+1}$ is determined by the smoothed hockey-stick stock-recruitment function (Froese, 2008), with parameter values $\varphi_1 = 420$ (112) and $\varphi_2 = 1.64$ (0.31) from Froese and Proelss (2010).

For age-specific prices $p_s$ we use European reference prices for 2010, which are the lowest prices at which fish imports into the European Union are allowed (EC, 1999, 2009). Age-specific maturity rates $\gamma_s$, weight-at-age in stock $w_s$, and age-specific natural survival rates $\alpha_s$ are taken from ICES (2011a). Relative age-specific catchabilities $q_s$ are estimated by means of average age-specific fishing mortalities for the years 2000–2010 (ICES, 2010b). Parameter values are given in Table A6.

**Table A6**
Parameter values used for age-cohort model of Eastern Baltic cod.

| Parameter | | Age | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Price $p(s)$ | Eur/kg | 0.000 | 0.350 | 0.350 | 0.447 | 0.447 | 0.447 | 0.636 | 0.636 |
| Weight $w(s)$ | Kg | 0.000 | 0.147 | 0.353 | 0.872 | 1.338 | 1.776 | 2.642 | 4.119 |
| Catchability $q(s)$ | | 0.00 | 0.09 | 0.47 | 0.87 | 0.94 | 0.78 | 1.00 | 1.00 |
| Survival rate $a(s)$ | | 1.00 | 0.82 | 0.82 | 0.82 | 0.82 | 0.82 | 0.82 | 0.82 |
| Maturity $\gamma(s)$ | | 0.13 | 0.36 | 0.83 | 0.94 | 0.96 | 0.96 | 0.96 | 0.98 |
| Initial stock numbers $x_0$ (2010) | Millions | 176.3 | 195.5 | 157.1 | 112.7 | 54.6 | 17.2 | 8.0 | 3.2 |

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