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**The Wealth of Ecosystems:
Valuing Natural Capital in the Context of Ecosystem Based Management**

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Abstract

This paper merges inclusive wealth accounting theory with ecosystem based management (EBM) to resolve two problems. First, we provide measures of an ecosystem's contribution to larger scale sustainability accounts by enabling ecosystems to be better included in inclusive wealth measures. We show the ecosystems are better thought of as portfolios of assets, and the portfolio's performance is depended on the performance of the underlying assets, including their interactions. Second, the wealth held in the ecosystem is an attractive headline index for EBM regardless of whether ecosystem wealth is ultimately included in a broader index. We generalize natural capital theory to approximate realized shadow prices (accounting prices) for multiple interacting stocks of biotic and abiotic assets and liabilities that comprise ecosystems. We apply our approach to the Baltic Sea ecosystem, focusing on the interacting community of three commercially important fish species; cod, herring and sprat. The accounting prices of the three species show decreasing patterns with larger stock accumulation. Our results reveal the “supporting value or regulation services” embodied in the shadow price of a species through its trophic influence on other species. Prey fish have greater shadow prices than would be expected based on market value and predatory fish have lower shadow prices than may be expected based on market value.

Key words: Natural Capital, Ecosystem Based Management, Green Accounting, Inclusive Wealth, Baltic Sea, Fishery

JEL codes: C6, E01, Q22, Q51, Q56, Q57

1. Introduction

Ecosystems are important stores of wealth. The 2014 Inclusive Wealth report suggests that 28% of global wealth is contained in ecosystems, which is certainly a lower bound (UNU-IHDP and UNEP 2014). Wealth accounting (e.g., inclusive/comprehensive/genuine wealth) is a rigorous economic paradigm for measuring sustainability, but the difficulty of measuring prices of natural capital has been its Achilles' heel (Smulders, 2012). Recently, there has also been a growing emphasis in the academic and policy sphere on “ecosystem based management” EBM, especially in the context of marine environment (Pitcher et al., 2009). EBM (Christensen et al., 1996; Pikitch et al., 2004) is a holistic management approach recognizing a full array of complexities within ecosystem that focuses on incorporating interactions between ecosystem components and examining a range of potentially contradictory indicators in an effort to capture different notions of the “health” of the ecosystem. The lack of a single goal-oriented “headline” indicator is problematic if EBM is to truly guide management. Merging inclusive/comprehensive wealth accounting theory with EBM solves two problems. First, it would provide measures of an ecosystem's contribution to larger scale sustainability accounts by enabling ecosystems to be better included in inclusive/comprehensive wealth measures. Second, the wealth held in the ecosystem is an attractive headline index for EBM regardless of whether ecosystem wealth is ultimately included in a broader index.

We contribute to the literature by jointly measuring realized shadow prices (accounting prices) for multiple interacting ecosystem components. Such prices reflect the limits of substitution opportunities among ecosystem components. Therefore, the prices capture cross-stock effects that imply the linear wealth index is not a weak sustainability index (Dasgupta, 2007), but rather one that recognizes the limits and opportunities of substitution. We then

develop a headline wealth index for an ecosystem. Our wealth index is suitable for inclusion into a national or regional sustainability wealth account or can serve as a standalone wealth index to assess the management of ecosystem as a whole.

We extend Fenichel and Abbott (2014) and Fenichel et al. (2016), FA, method to approximate realized shadow prices for multiple interacting stocks of natural capital. FA enables valuation of natural capital assets under the current management scheme without requiring the analyst to assume optimizing institutions. Moreover, FA prices are scarcity measures that account for feedbacks from human behavior and institutions. We generalize FA's single stock derivation to the case of the multiple interacting stocks of biotic and abiotic assets and liabilities that comprise ecosystems.

We apply our approach to the Baltic Sea ecosystem, focusing on the commercial fishing industry and three central fish species; cod (*Gadus morhua*), herring (*Clupea herengus*) and sprat (*Sprattus sprattus*). The depletion of the Baltic Sea cod in the 1980s/1990s resulted in major regime shift from a predator- to prey-dominated ecosystem (Alheit et al., 2005; Möllmann et al., 2009). To capture predator-prey dynamics and vessel responses, which are conditioned on the regulatory regime, we adopt the vessel level fishing choice model in Hutniczak (2015). Poland manages all three species by binding individual allocations of the total allowable catches (TAC) since 2014. Approximately, 80% of the 2014 Polish Baltic Sea fishery revenue came from these three species. In the model, the fishing fleet consists of vessels that optimize individual behavior subject to regulations, feasibility constraints (maximum days the vessel can spend at sea), owned capital, production structure (in the form of an estimated distance function), and individual technical efficiency. The biological sub-model describes the feedback from the ecosystem based

on interacting components derived from established food web links. The economic component allows estimation of the profit-maximizing response to the quota allocations based on the established harvest control rule.

Using this relatively complex bioeconomic model, we develop a simplified, reduced form simulation model that generates the stock-dependent predictions of harvest, profit, and growth rate needed for our asset pricing approach. We then generalize the collocation approach in FA to estimate the “capital gains” term in the numerator of the shadow price equation through polynomial approximation of the value function. Lastly, we approximate the accounting prices and calculate the inclusive wealth values. As expected, the accounting prices of the three species show globally decreasing patterns with larger stock accumulation, *ceteris paribus*. Our results reveal the “supporting value (or regulating services)” embodied in the shadow price of a species through its trophic influence on other species. Prey fish have greater shadow prices than would be expected based on market value and predatory fish have lower shadow prices than may be expected based on market value.

Our approach is relevant to economists interested in sustainability and green accounting and to natural resource managers interested in EBM. Our contribution advances the field towards an inclusive vision of wealth for measuring sustainability. Furthermore, it shows that economic measures of sustainability are not strictly weak. Rather in advancing Barbier’s (2011) notion of “capital sustainability” with multiple interacting stocks, even the linear wealth index approach captures the limits and opportunities of substitution when prices are accurately measured. In addition, the empirical analysis adopted in the paper can be easily applied for other complex EBM models. The suggested two step approximation—curve fitting with polynomial

approximation and numerical functional approximation—could provide a practical guidance for other research.

2. Valuing the Natural Capital of an ecosystem

Natural capital asset prices are a requirement to operationalized wealth accounting (Dasgupta, 2014; Hamilton & Hartwick, 2014; UNU-IHDP & UNEP, 2014; World Bank, 2011). The SEEA accounting framework (United Nations et al., 2012) and Barbier (2011; 2013) suggest that ecosystems a whole can be considered assets and changed in the wealth of ecosystems can be valued as such. However, ecosystems are better thought of as a fund or portfolio. The performance of the ecosystem “fund” is a function of the performance of the underlying assets. However, unlike a financial fund, the capital stocks help in an ecosystem interact and affect each other’s performance. Therefore, it is important to disaggregate the ecosystem into the most important stocks in order to track the wealth held in an ecosystem. We provide a pricing approach for natural capital assets that generalizes Fenichel and Abbott (2014) and Fenichel et al. (2016), who previously adapted the capital asset pricing approach of Jorgenson (1963).¹

Let $s_i(t)$ be the i -th natural capital stock of N multispecies ecosystems. The state of natural capital changes over time (t) is²:

$$\frac{ds_i}{dt} = \dot{s}_i = G(\mathbf{S}) - f(\mathbf{S}, x(\mathbf{S})), \quad (1)$$

¹ Our generalized approach is not restricted to natural capital assets. It is suitable for recovering shadow prices for stocks of capital that strongly interact and for which strong markets do not exist. Human and real capital may also fall into this category, but we leave this for future investigation.

² Through the whole text, we adopt the time derivative as dot notation, e.g. $\frac{ds_i}{dt} = \dot{s}_i$ while the stock derivative as subscript, e.g., $\frac{dW}{ds_i} = W_{s_i}$ by following a conventional way if there is no notational confusion.

where $\mathbf{S}(t) = (s_1(t), s_2(t), \dots, s_N(t))$ is an array of multiple stocks, G is a growth or recharge function, f is an anthropogenic impact function, and x is an economic program (Fenichel & Abbott, 2014; Fenichel et al., 2016a; Fenichel et al., 2016b). In fishery, for example, G is a biological system including prey-predator relations and f is fishing behavior under the given regulation regime, which will be parametrically defined in the economic program. Define $W(\mathbf{S}(t), x(\mathbf{S}(t)))$ as an index of the net benefits, or dividends, flowing to society as net Fisherian income (Fisher, 1906) at time, t . We assume that $W(\mathbf{S}, x(\mathbf{S}))$ is measured in stable monetary terms so that discounting at a constant exponential rate is justified (Dasgupta et al., 1999). At a time t , the present value of net benefits is:

$$V(\mathbf{S}(t)) = \int_t^{\infty} e^{-\delta(\tau-t)} W(\mathbf{S}(\tau), x(\mathbf{S}(\tau))) d\tau, \quad (2)$$

by adopting $\mathbf{S}(\tau)$ of Equation (1). The term δ is the social discount rate.

The derivative of W with respect to a stock s_i includes the feedback through the economic program as $W_{s_i} = \frac{dW}{ds_i} = \frac{\partial W}{\partial s_i} + \frac{\partial W}{\partial x} \frac{dx}{ds_i}$ (Fenichel & Abbott, 2014; Fenichel et al., 2016a).

Adopting W_{s_i} , the derivative of V with respect to a stock s_i is:

$$\frac{dV}{ds_i} = \frac{\partial V}{\partial s_i} + \frac{\partial V}{\partial W} \frac{dW}{ds_i} = \frac{\partial V}{\partial s_i} + \frac{\partial V}{\partial W} \left(\frac{\partial W}{\partial s_i} + \frac{\partial W}{\partial x} \frac{dx}{ds_i} \right). \quad (3)$$

The accounting price for a natural capital stock s_i , conditional on the existing institutions, is defined as:

$$p_i(\mathbf{S}(t)) \equiv \frac{\partial V(\mathbf{S}(t))}{\partial s_i}. \quad (4)$$

From the relation in Equation (3), the definition (4) provides:

$$p_i(\mathbf{S}) = \frac{\partial V}{\partial s_i} = \frac{dV}{ds_i} - \frac{\partial V}{\partial W} \left(\frac{\partial W}{\partial s_i} + \frac{\partial W}{\partial x} \frac{dx}{ds_i} \right). \quad (5)$$

It is noteworthy that p_i is a function of all stocks, \mathbf{S} , rather than a single stock of s_i through the feedback process in change of W and economic program of x . This means the accounting price of p_i includes cross-stock effects.

Following Dasgupta and Mäler (2000) and Arrow et al. (2003) and adopting the definition (4), we differentiate $V(\mathbf{S}(t))$ with respect to t and express it as:

$$\frac{dV}{dt} = \delta V - W(\mathbf{S}, x(\mathbf{S})) = \sum_{i=1}^N \frac{\partial V}{\partial s_i} \frac{ds_i}{dt} = \sum_{i=1}^N p_i \dot{s}_i. \quad (6)$$

Equation (6) states that the time rate of change of the present value of benefits is equal solely to the effect from changes in the natural capital stocks (Fenichel & Abbott, 2014). Rearranging the terms in Equation (6), we have the current value Hamiltonian (CVH) as:

$$\delta V = W(\mathbf{S}, x(\mathbf{S})) + \sum_{i=1}^N p_i \dot{s}_i = H(\mathbf{S}, x, \mathbf{p}) = H(\mathbf{S}, \mathbf{p}), \quad (7)$$

where $\mathbf{p} = (p_1(\mathbf{S}), p_2(\mathbf{S}), \dots, p_N(\mathbf{S}))$ is an array of accounting prices as a function of stocks, \mathbf{S} . Equation (7) is the CVH evaluated with the economic program $x(\mathbf{S})$, composed of the flow of current benefits $W(\mathbf{S}, x(\mathbf{S}))$, and the value of increments to the stocks, $\sum_{i=1}^N p_i \dot{s}_i$.³

Dividing δ on both sides, Equation (7) yields:

$$V = \frac{1}{\delta} (W(\mathbf{S}, x(\mathbf{S})) + \sum_{i=1}^N p_i \dot{s}_i). \quad (8)$$

Differentiating Equation (8) with respect to s_i ,

$$p_i = \frac{\partial V}{\partial s_i} = \frac{1}{\delta} \left(\frac{\partial W}{\partial s_i} + \sum_{j=1}^N \left(\frac{\partial p_j}{\partial s_i} \dot{s}_j + p_j \frac{\partial \dot{s}_j}{\partial s_i} \right) \right)$$

³ Note that we manage a time autonomous case here. A generalization to non-autonomous case can be derived from a similar way referring to Asheim (2000).

$$= \frac{1}{\delta} \left(\frac{\partial W}{\partial s_i} + \sum_{i \neq j}^N \left(\frac{\partial p_j}{\partial s_i} \dot{s}_j + p_j \frac{\partial \dot{s}_j}{\partial s_i} \right) + \dot{p}_i + p_i \frac{\partial \dot{s}_i}{\partial s_i} \right) \quad (9)$$

Rearranging Equation (9), we have the multiple stock version of the natural capital asset price equation in Fenichel and Abbott (2014):

$$p_i = \frac{\frac{\partial W}{\partial s_i} + \dot{p}_i + \sum_{i \neq j}^N \left(\frac{\partial p_j}{\partial s_i} \dot{s}_j + p_j \frac{\partial \dot{s}_j}{\partial s_i} \right)}{\delta - \frac{\partial \dot{s}_i}{\partial s_i}}. \quad (10)$$

Compared to the single stock version of price equation (Fenichel & Abbott, 2014; Fenichel et al., 2016a; Fenichel et al., 2016b), Equation (10) has an additional term of cross stock effect, $\sum_{i \neq j}^N \left(\frac{\partial p_j}{\partial s_i} \dot{s}_j + p_j \frac{\partial \dot{s}_j}{\partial s_i} \right)$. Eq (10) enables us to develop a price function over all possible values of the state variable on the current economic program in a single step. This leads the inclusive wealth as the sum of product of shadow price and stock asset (Dasgupta, 2014) as:

$$IW = \sum_{i=1}^N p_i s_i, \quad (11)$$

and Eq (10) enables us to track the changes in the natural capital assets contributions to inclusive wealth through time.

From the differential equation form presented in Equation (8), V and $V_{s_i} = p_i$, functional approximations, the collocation method can be adopted to figure out p_i numerically (Miranda & Fackler, 2002). Following the V-approximation approach suggested in Abbott et al. (2016), suppose we have the size M of data for W and \dot{s}_i over the stock domain of the Chebyshev nodes, $\mathbf{S}(t) = (s_1(t), s_2(t), \dots, s_N(t))$ at a time point t , i.e., a $M \times (N + 1 + N)$ data matrix.⁴ Then, we define φ_i as the $M \times (d_i + 1)$ basis matrix of d_i -th degree evaluated at the M numbers of stock combinations. Adopting the tensor product basis, the functional basis for real valued function is

⁴ It is not necessary for all data to be on Chebyshev nodes. For the convenience of description, we assume that the data is collected (or generated) over the Chebyshev nodes used for Chebyshev polynomial approximation.

$\varphi = \varphi_N \otimes \varphi_{N-1} \otimes \cdots \otimes \varphi_1$ where \otimes is the Kronecker product. Due to the orthogonality and multiple differentiability of the basis function, the Chebyshev polynomial can provide a convenient way of approximation (Sauer, 2014). Returning back to Equation (8), let $V(\mathbf{S}) = \varphi(\mathbf{S})\beta$ where $\varphi(\mathbf{S})$ is the $M^N \times \prod_{i=1}^N (d_i + 1)$ Chebyshev polynomial basis evaluated at the stock combination \mathbf{S} and β is an $\prod_{i=1}^N (d_i + 1) \times 1$ unknown coefficients vector. From the orthogonality of Chebyshev basis, $p_i = \frac{\partial \varphi(\mathbf{S})}{\partial s_i} \beta$, Equation (8) becomes $\delta \varphi(\mathbf{S})\beta = W(\mathbf{S}) + \sum_{i=1}^N \text{diag}(\dot{s}_i) \frac{\partial \varphi(\mathbf{S})}{\partial s_i} \beta$. If this is the exactly determined case ($M = d_i$), we can get the β from:

$$\beta = \left(\delta \varphi(\mathbf{S}) - \sum_{i=1}^N \text{diag}(\dot{s}_i) \frac{\partial \varphi(\mathbf{S})}{\partial s_i} \right)^{-1} W(\mathbf{S}). \quad (12.1)$$

In a case of over-determined ($M \geq d_i$ for at least one i), we can derive β from the least squares:

$$\beta = \left(\left(\delta \varphi(\mathbf{S}) - \sum_{i=1}^N \text{diag}(\dot{s}_i) \frac{\partial \varphi(\mathbf{S})}{\partial s_i} \right)^T \left(\delta \varphi(\mathbf{S}) - \sum_{i=1}^N \text{diag}(\dot{s}_i) \frac{\partial \varphi(\mathbf{S})}{\partial s_i} \right) \right)^{-1} \times \left(\delta \varphi(\mathbf{S}) - \sum_{i=1}^N \text{diag}(\dot{s}_i) \frac{\partial \varphi(\mathbf{S})}{\partial s_i} \right)^T W(\mathbf{S}) \quad (12.2)$$

With a single stock version of Equation (10), Fenichel and Abbott (2014) suggest the \dot{p} -approximation (by setting $\dot{p} = \varphi(s)\beta$) and Fenichel et al. (2016) provide the p -approximation (by letting $p = \varphi(s)\beta$). We, however, suspect that the computational burden for p - and \dot{p} -approximation is greater than V -approximation in the multi-dimensional case due to its mathematical complexity and thus, a more high chance to have singularity and curse of dimensionality. Due to its simplicity and relatively low computational burden, we adopt the V -

approximation for our analysis. We use the R-package ‘*capN*’⁵ (Yun et al., 2016) for the Baltic Sea fishery analysis in the next two sections.

3. Baltic Sea Fishery: Multispecies Interaction Model

To validate the suggested capital theoretic framework in Equation (8) and its numerical approximation, we adopt the multispecies interaction model of the Baltic Sea fishery from Hutniczak (2015). The model in Hutniczak (2015) is a micro-macro link simulation model based on individual vessel’s fishing behavior under the given regulations and the vessels’ aggregated impacts on ecosystem. In the model, the fishing fleet consists of vessels that maximize vessel net revenue subject to regulations, feasibility constraint (maximum days the vessel can spend at sea), owned capital, production structure (in form of distance function estimated, based on available log book data), and individual technical efficiency (derived from distance function estimates). Effectively this is an agent-based model with a finite number of agents. Therefore, the simulations generate the “data” (W and \hat{s}_i over the interested combinations of stock domains) as bumpy data surfaces rather than a smooth well-behaving global surface. Since it is rarely possible to define an explicit simultaneous system of equations for ecosystems and EBM,⁶ a simulation based model such as agent-based model could be more realistic and practical alternative. To implement natural capital valuation, we first fit the generated data with polynomial approximation and then, apply the suggested methods over the smoothly fit data of

⁵ “*capN*” provides the full functions for the Chebyshev polynomial approximations: the V -approximation for single and multiple stocks, and the p - / \hat{p} -approximation for single stock cases. For the time of analysis (May, 2016), we adopt the beta testing version 0.0.2 of “*capN*” package.

⁶ In here, we are not denying an existence of well-behaving system of equations. What we assume is the difficulty of defining *ex-ante* equations of ecosystems and EBM.

W and \hat{s}_i . We believe that the smoothly fit curves are the *intent* of policy and the policy is not purposefully producing lumpy behavioral and profit results.

-- Figure 1 about here --

We investigate the central Baltic Sea as a case study, with its interacting fish community dominated by three species: cod, herring and sprat (ICES, 2014). Cod plays an important structuring role in this ecosystem as a predator of herring and sprat. By contrast, herring and sprat, species belonging to the clupeid family, prey on cod eggs and impact cod growth, thus creating a feedback loop that strongly ties these species together (Figure 1). We focus on Polish fleet as one of the major fleets in the Baltic Sea.

3.1. Biological Process

The purpose of the multispecies interaction model is to realistically simulate changes over time in stock sizes by taking the ecosystem structure into consideration. The biological model includes three separate dynamically updating submodels for cod, herring and sprat linked through predation. The predator species (cod) is a cause of predation mortality (P) whereas the prey availability (herring and sprat) is influencing the predator's consumption rates and its growth (G). For simplicity, we assume that environmental factors are invariant such as the sensitivity of cod to the salty water inflows from the North Sea.

The model suggests a sufficient overlap between species distribution range to model the stocks as aggregated biomass, i.e. there are no localized populations for which spatial distribution is mutually exclusive. The population dynamics in the base simulation model follow the standard age-structured modeling methodology (Tahvonen, 2009). Disaggregating the adult population into multiple age categories is assumed to better describe age-structured management

that imposes minimum mesh size and minimum landing sizes on the fishing fleets in the region; therefore, welfare gain estimations are more precise (Quaas et al. 2013; Thøgersen & Hoff 2013). The model is in discrete time in order to keep with biological reproduction (Finnoff & Tschirhart, 2003). The biological model is closely inspired by work of Heikinheimo (2011), whereas includes several updating features based on recent development in the literature. The detail models and parameters are described in the appendix.

3.2. Economic Program

The Baltic Sea fishery is an important industry in the coastal area of northern Poland and relies on cod, herring and sprat as a main target species in about 79% in revenue terms (STECF, 2015). The depletion of the Baltic Sea cod in the 1980s/1990s resulted in major regime shift from predator- to prey-dominated ecosystem what makes it an interesting case study of human impact on multispecies environment (Alheit et al., 2005; Hutniczak, 2015). Policy makers responded to the shift with major changes in management (Alheit et al., 2005; Möllmann et al., 2009) that can be evaluated in terms of altered value of this complex ecosystem (Figure 2).

-- Figure 2 about here --

The key regulatory tools are set annually total allowable catches (TAC) based on a single species stock assessment and target fishing mortalities. The allocation between the European Union (EU) members is based on the principle of relative stability, which implies that each country receives a fixed share of each TAC (Churchill & Owen, 2010). The distribution of national TAC between vessels or individual fishermen is the responsibility of individual countries. Poland, a member of the EU since 2004, manages all three species by binding

individual allocations of TAC since 2014. The total allowance is divided among eligible units according to the coefficient that depends on the vessel size.

3.3. Profit Maximization of Heterogeneous Vessels

The fishing fleet consists of vessels that optimize individual behavior subject to regulations, owned capital, individual technical efficiency and current stock abundance. In this context, the regulation of particular validity is the management plan allocating quotas for each species affecting harvest now and in the future by impact on the stocks. Each unit employs effort as input and attempts to achieve input efficiency. The individual vessel is considered here a decision unit optimizing its own behavior over time that is simplified to assume profit maximization.

Hutniczak (2015) adopts the multiproduct distance function with input oriented specification (Shephard, 1970) as an effort requirement function. For individual vessel ($n \in N$), fishing effort can be presented by the translog function:

$$\begin{aligned}
 \ln(e_{n,t}) &= \sum_{i \in I} \alpha_i \ln(h_{i,n,t}) + \alpha_k \ln(k_n) \\
 &+ \frac{1}{2} \sum_{i \in I} \sum_{i' \in I} \alpha_{ii'} \ln(h_{i,n,t}) \ln(h_{i',n,t}) + \frac{1}{2} \alpha_{kk} \ln(k_n) \ln(k_n) \\
 &+ \sum_{i \in I} \alpha_{ik} \ln(h_{i,n,t}) \ln(k_n) + u_n + u_t + v_{n,t} \\
 &= -TL(h_{n,t}, k_n) + u_n + v_{n,t}, \tag{13}
 \end{aligned}$$

where e is effort of fishing, $i \in I = \{c, h, s, o\}$ is species for cod, herring, sprat and others, k is vessel power, h is harvested biomass, u_n is individual vessel fixed effect, and $v_{n,t}$ is stochastic term. To reflect the direct and indirect effects of stock size on catch, we use harvest transformed into partial fishing mortality (Pascoe et al, 2007) which in practical terms means that harvest is divided by normalized stock variables derived as harvestable biomass (Hutniczak,

2015). In addition, all variables in Equation (13) are normalized by their means so that each variable is a relative distance from its mean.⁷ All coefficients and technical efficiency were estimated using individual fixed effects.

With the estimated coefficients of Equation (13), the profit maximization model of heterogeneous vessel assumes the upper bound for effort denoted by \widetilde{e}_n ⁸ that can be considered a feasibility constraint. Thus, the harvest plan is adjusted from initial quota allocation according to economic incentives (profitability criteria) and subject to effort restriction (feasibility criteria). Assuming constant prices and adding a cost variable, the profit maximization problem is:

$$\max_{x_j} (\sum_{j \in J} p_{j,n} x_{j,n} + p_{o,n} x_{o,n}) - \exp(-TL(h_{n,t}, k_n) + u_n + u_t) c_{v,n} - c_f, \quad (14)$$

s.t.

$$0 \leq x_{j,n} \leq IVQ_{j,n} \quad : \text{harvest constraint}$$

$$0 \leq \exp(TL(h_{n,t}, k_n) + u_n + u_{2012}) \leq \widetilde{e}_n \quad : \text{effort constraint}$$

where x_j is harvested quantity for species $j \in \{c, h, s\}$, p_i is price, subscript o is all other species, $c_{v,n}$ is variable cost per unit effort, and c_f is fixed cost. Following Hutniczak (2015), we use 2008-2012 Polish fishery panel data for efficiency estimation and adopt the 2012 fleet structure to implement the optimization of Equation (14) for simulation. The estimation procedure and the parameters adopted in the model are described in Appendix B.

⁷ For example, $h = \frac{x}{B} / \left(\frac{x}{B}\right)$ where x is quantity of harvest, B is biomass index normalized at 2014, and $\left(\frac{x}{B}\right)$ is the mean of $\frac{x}{B}$.

⁸ In the empirical analysis, two types of vessels (large vessels (longer than 12 meters) and small vessels (otherwise)) are adopted. For a large vessel, \widetilde{e}_n is given as 160 days while 90 days does for a small vessel.

3.4. Simulation Data Generation

In section 2, we assume that the $M \times (N + 1 + N)$ size of data set of W and \dot{s}_i from various combinations of stocks are presented before implementing the suggested V - approximation of Equation (8) and Equation (12). In reality, however, such data are rarely available. For our analysis, we perform the multispecies interaction model through the various combinations of stocks to simulate W and \dot{s}_i using Poland fishing logbook data described in Appendix B. In our case, the monetary terms of W is the net revenue from harvesting cod, herring and sprat, and the \dot{s}_i is the change of stocks including fishing. Since available data covers only short time period with limited combinations of biomass abundance, we rely on only 2012 data is available for figuring out all parameters of the biological process in Appendix A. We simulate 411 Polish fishing vessels (189 vessels longer than 12 m and 222 vessels shorter than 12 m) in 2012 as described in Appendix B. To represent the whole Baltic Sea fishing behavior and use fixed multipliers,⁹ the ratio between the 411 and the Baltic Sea overall for each variable, to the simulated variables.

To determine approximation domains, we first investigate the stock changes for 100 years starting from the stocks of year 2012, [174.939, 1,302.509, 1,752.787] (1,000 tons) for cod, herring and sprat (yearly stock fluctuations in Figure 2). Figure 3 presents the time dynamics of 100 years.¹⁰

-- Figure 3 about here --

About the 50th year and after, the stocks of three species converge to the stable level of stocks. After confirming the stability of convergence with 150 years, we derived the steady state as the

⁹ These multipliers can be provided upon requests.

¹⁰ With more longer periods, up to 200 years, we confirmed that the 100 years are enough length to show the steady state.

mean of stocks from 51st to 100th years; $ss=[526.932, 1,142.813, 1,213.527]$ (1,000 tons) for cod, herring and sprat.

Based on the steady state and 2012 conditions, we set the simulation domain of the multispecies interaction model as the lower bound = [130, 60% of the herring ss , 60% of the sprat ss] and the upper bound = [560, 140% of the herring ss , 160% of the sprat ss]. It is noteworthy that fishing is shut down when a species reach the moratorium level about [100, 580, 550] (1,000 tons) for cod, herring and sprat.¹¹ The lower bound, therefore, is determined to avoid the moratorium stock level safely, which creates discrete jumps in W and \dot{s}_i surfaces.¹² Since the 2012 stock of cod (174,939 tons) and the recent historical stocks in Figure 2 were much lower than the steady state level (526,932 tons), we set up 130,000 tons as the lower bound to make the cod range more meaningful. On the other hand, due to its abundant historical stocks of sprat, we set up the upper bounds as 140% and 160% of the steady state for herring and sprat. With the given stock domains, we generate [20 x 20 x 20] Chebyshev polynomial nodes and simulate profit (W) and growth rate (\dot{s}_i) shown in Figure 4.

-- Figure 4 about here --

As expected, more stocks for three species provide higher profits and more cod derives less herring and sprat.

Since we simulate the Baltic Sea fishery from the fishing behavior of 411 Polish vessels, the interpretation of simulation model needs to be considered carefully. For this purpose, we calculate the TAC utilization (the percentage of harvest/TAC) from the simulation results. Figure 5 show the histogram of utilizations from the 8,000 combinations of stock nodes.

¹¹ Fishing is not allowed the stock levels below the moratorium level determined by the spawning stock biomass. The presented bound of [100, 580, 550] (1,000 t) is the approximated numbers in stock biomass.

¹² In numerical approximation, the classic Chebyshev polynomial approximation adopted in this paper is not appropriate to simulate discontinuous or non-smooth functions (Mace, 2005).

-- Figure 5 about here --

In Hutniczak (2015), the historical TAC utilization was 68% ~ 99% for cod, 39% ~ 122% for herring, and 41% ~ 95% for sprat during year 2008 to year 2012. Our simulation results in Figure 5 suggests the TAC utilization from our model fall within realistic ranges.

4. Results and Discussion

We fit the data generated data in Figure 4 to a multivariate polynomial in order to smooth the surfaces for W and \dot{s}_i . This smoothing process is meant to provide reasonable derivatives and enables us to abstract from the discrete nature of the fishing industry. As noted in Section 3, the simulated data is likely to provide (sufficiently) well approximated values. It, however, includes many bumpy spots that make it difficult to numerically handle the multivariate approximation. Smooth functions bump up against the curse of dimensionality at higher dimensions (CITE). Assuming well-behaving, but unknown, ex-post surfaces of W and \dot{s}_i , we implement a multivariate polynomial least squares regression (Fig 6).

-- Figure 6 about here --

Instead of using [20 x 20 x 20] Chebyshev polynomial nodes described in Section 3.4, in Figure 6, we represent the fitted curves from [3 x 3 x 3] order polynomials from the evenly gridded 2,873 data nodes of 70% of and 110% of the steady state. All curves are highly well-fitted with the adjusted R2 (0.9981, 0.9844, 0.9948, 0.9981) and the root mean squared errors (RMSE: 0.4052, 2.2090, 3.8796, 4.9706) for profit and each of \dot{s}_i . In the natural capital valuation process, we fit the [20 x 20 x 20] Chebyshev polynomial nodes and the goodness of fit from [3 x 3 x 3]

order polynomials is that the adjusted R2 are (0.9976, 0.9918, 0.9947, 0.9974) and the RMSEs are (0.4905, 2.3674, 5.0729, 8.2837).

Since this relatively low order of polynomials ([3 x 3 x 3]), we can achieve good enough fit, we implement the Chebyshev polynomial approximations for Equation (12). With [3 x 3 x 3] Chebyshev polynomial approximation, the accounting prices of three species are presented in Figure 7.

-- Figure 7 about here --

Figure 7 approximates from the fitted data with the multivariate polynomials. The 8,000 generated data includes many bumpy spots over profit and the growth rate surfaces. To increase the orders of polynomials to approximate these surfaces more smoothly, we can observe oscillations. These oscillations are getting worse with higher orders (Gottlieb & Shu, 1997; Mace, 2005). In addition, it is noteworthy that the error convergent maximum orders for the fitted curves in the first two columns are [3 x 3 x 3] due to the orders of fitted curves. If we increase the orders higher than [3 x 3 x 3] by increasing the orders of fitted curves, the Chebyshev polynomials provide higher error sizes and oscillations can be appeared. From our data, we observe the Gibbs phenomenon from both cases.

From Figure 7, we configure three important accounting price behaviors. First, prices are decreasing for all three species when holding the other two. As expected in general price curves, our analysis achieves the negative slope of price curves, i.e, price decreases as quantity increases. Second, cross-stock effects exist. At the first column of Figure 7, we can observe there are nonlinear price changes along with stock combinations. In multiple stocks analysis, the price curves include the cross-stock effects terms, $\sum_{i \neq j}^N \left(\frac{\partial p_j}{\partial s_i} \dot{s}_j + p_j \frac{\partial \dot{s}_j}{\partial s_i} \right)$ in Equation (10), that creates nonlinear substitution and complements among stocks. When holding one species stock, then we

can observe this nonlinear effect more clearly as shown in Figure 8. In Figure 8, each stock is fixed at the steady state for the purpose of simplicity.

-- Figure 8 about here --

Lastly, the shadow price of cod is negative over large stock levels while the shadow price around steady is close to the average of 2012 ex-vessel price. In the Baltic Sea ecosystems, herring and sprat are prey and provide provision and regulating services. Cod is a multiple-use species providing a direct provisioning service in the current management setting (Fenichel et al., 2010; Horan & Bulte, 2004; Rondeau, 2001; Zivin et al, 2000). The multiple use species creates the potential for ecosystem externalities (Crocker & Tschirhart, 1992), which is reflected in the accounting price. Due to the possibility of non-convexities in our analysis, the accounting prices in the results may reflect local dynamics rather than global dynamics.

Following Equation (11), we calculate the inclusive wealth according to the time dynamics in Figure 3 shown in Figure 9. Since there are steady state later 50th year, we present only first 60 years dynamics of inclusive wealth.

-- Figure 9 about here --

From Figure 7 and 8, we can see that the accounting price of cod is positive with smaller cod but larger herring and sprat stocks while the opposite happens for herring and sprat. The total inclusive wealth are negative for the first several years. After that, the inclusive wealth becomes positive due to positive accounting prices of herring and sprat. At the year 2012, herring and sprat stocks are relatively high but cod stock is a way below from the steady state. In Figure 10, we calculate the inclusive wealth and estimated V-function value for the historic stocks of year 2003 to 2013.

-- Figure 10 about here --

5. Conclusion

This paper merges inclusive wealth accounting theory with ecosystem based management (EBM) to numerally measure the value of ecosystem. Generalizing the FA method, we suggest an approach to approximate realized shadow prices for multiple interacting stocks of biotic and abiotic assets and liabilities that comprise ecosystems. We apply our approach to the Baltic Sea ecosystem, focusing on the commercial fishing industry and three central fish species; cod, herring and sprat. Our approach is relevant to economists interested in sustainability and green accounting and to natural resource managers interested in EBM. Our contribution advances the field towards an inclusive vision of wealth for measuring sustainability.

Since this draft is in a preliminary step of the whole research, we expect to include three additional contents in near future. First, we will discuss more details on the results focusing on interpretation of inclusive wealth and estimated V-function values. Second, we will derive deep policy implication for the EBM of Baltic Sea and for general EBM policy. Last, additional analysis to configure policy frictions, e.g. comparison between the current regime and tradable permits system, could be discussed.

Appendix A: Biological Model

The biological model includes three separate submodels for cod, herring and sprat linked through predation. The model parameters are derived based on the Report of the Baltic Fisheries Assessment Working Group by the International Council for the Exploration of the Sea (ICES, 2014), unless noted otherwise. ICES provides the annual stock assessment of major Baltic Sea species including a wide array of time-series indicators for species of our interest.

Each submodel includes 8 age classes, with the last category covering adults of age 8 and higher. Let $i, i \in (c, h, s)$ denote the specific species that are included in the model: cod, herring and sprat, respectively. Let $a, a \in [1, 8]$ denote age class and t the time period. The modeled spawning stock biomass (SSB, in thousands of tons) is derived from the latest estimation of maturity ogive ($\zeta_{i,a}$) and weights at age in stock ($w_{i,a}$) available in table A.1.:

$$SSB_i = \sum_{a=1}^8 \zeta_{i,a} w_{i,a} x_{i,a}. \quad (\text{A.1})$$

Following the Benchmark Workshop on Baltic Multispecies Assessment (ICES WKBALT, 2013) approach, weight of adult cod is found significantly impacted by the amount of prey available, whereas weight of recruitment is based on weight of cod in spawning stock (w_c SSB). This is represented by the following equations:¹³

$$w_{c,a,t} = \psi_1 + \psi_2 \ln(w_c \text{SSB}); a \in [2] \quad (\text{A.2a})$$

$$w_{c,a,t} = w_{c,a-1,t-1} \left(\theta_{a-1} + \frac{(\sum_{i' \in (s,h)} \sum_{a'=1}^8 x_{i',a',t})^n}{(\sum_{i' \in (s,h)} \sum_{a'=1}^8 x_{i',a',t})^n + D_{sh}^n} \right); a \in [3,8]. \quad (\text{A.2b})$$

The estimates are available in Table A.2.

¹³ Cod weight estimates are based on 1991-2012 data (ICES, 2013). The equations are estimated jointly with robust standard errors. The R^2 for the joint equation is 0.68.

Table A.1: Maturity ogive and weights at age in stock.

Age	1	2	3	4	5	6	7	≥ 8
Maturity								
Cod	0.00	0.13	0.36	0.83	0.94	0.96	0.96	0.98
Sprat	0.17	0.93	1.00	1.00	1.00	1.00	1.00	1.00
Herring	0.00	0.70	0.90	1.00	1.00	1.00	1.00	1.00
Weight [g]^a								
Cod		179	366	827	997	1279	1898	2216
Sprat	5	9	10	11	11	11	12	12
Herring	13	22	28	32	37	41	46	51

Note: ^a average for 2008-2013. Source: ICES 2014.

Table A.2: Cod growth function coefficients.

Coefficient	Value	SE	p-value
ψ_1	0.223	0.052	0.019
ψ_2	0.132	0.015	0
ϑ_2	1.534		
ϑ_3	1.820		
ϑ_{4+}	0.818		

Note: Based on 2008-2013 data. Source: ICES 2014.

The endogenously determined recruitment of age class one dependent on spawning stock biomass ($SSB_{i,t}$) is given, following Voss et al. (2012), by Ricker (1954). In addition, cod recruitment has been found to be dependent on the environmental conditions described by the average deep-water salinity (Heikinheimo, 2008), and therefore the recruitment function in form of modified Ricker curve incorporates environmental variable denoted by Env .¹⁴ It stresses cod sensitivity to the salty water inflows from the North Sea that are irregular. This type of stock-recruitment relationship is considered to be the best suited for the major Baltic Sea stocks. The functional forms for recruitment are given as follows:

¹⁴ The deep-water salinity index was derived as the average annual salinity in the three major Baltic Sea deeps, Bornholm Deep (station BY5), Gotland Deep (station BY15) and Landsort Deep (Station BY31) at depths of a minimum of 90 m for BY5 and a minimum of 100 m for BY15 and BY31 for the period between April and August (spawning season). Heikinheimo (2008) only used Landsort Deep, whereas the major spawning areas are Bornholm and Gotland Deep (Margonski et al., 2010); therefore, the original method was updated, similar as in Thøgersen et al. (2013). The index used standardized variables with a mean of zero and a standard deviation of one. The data that have been used within this paper come from the SMHI's database SHARK (Svenskt HavsARKiv). The data have been generated within the Swedish coordinated environmental monitoring program by the Swedish EPA.

$$x_{i,a=2,t+2} = SSB_{it} \exp(\alpha_i + \beta_i SSB_{it} + \gamma Env_t), i \in (c) \quad (A.3a)$$

$$x_{i,a=1,t+1} = SSB_{it} \exp(\alpha_i + \beta_i SSB_{it}), i \in (h, s) \quad (A.3b)$$

where $x_{i,a,t}$ denotes a population of species i at age a and time t in number of fish (in millions of specimens), and SSB_{it} represents spawning stock biomass of species i at time t . The parameters are estimated using 1974-2012 values.¹⁵ Because the ICES provides estimates for recruitment of cod at age two, equation (A.3a) includes a two-period lag. However, the model considers recruits of cod at age one. Therefore, similar to Quaas et al. (2013), juvenile cod is assumed to have constant mortality and is derived prospectively (from year ahead cod age two) with no harvest at age one. Thus, the impact of cannibalism on juvenile cod populations is indirectly incorporated in the recruitment function. The recruitment is estimated in linearized logarithmic form:

$$\ln(x_{i,a=2,t+2}/SSB_{it}) = \alpha_i + \beta_i SSB_{it} + \gamma Env_t + \varepsilon_{i,t}, i \in (c) \quad (A.4a)$$

$$\ln(x_{i,a=1,t+1}/SSB_{it}) = \alpha_i + \beta_i SSB_{it} + \varepsilon_{i,t}, i \in (h, s). \quad (A.4b)$$

The equations (A.4a) and (A.4b) are estimated jointly using Seemingly Unrelated Regression (Zellner, 1962) to test correlation of residuals between equations. The Breusch-Pagan test of independence (Breusch and Pagan, 1980) results ($\chi^2=13.574$, $p=0.0035$) suggest that estimating recruitment of all species jointly performs better than single equation ordinary least square. The parameters of the stock recruitment relationship for each species, together with standard errors, are presented in Table A.3. The majority of the coefficients are significant at the 99% confidence level, indicating good data fit. The covariance matrix of the disturbances is presented in Table A.4.

¹⁵ The ICES report (ICES, 2013) provides additional 1966-1973 data for cod. However, for joint estimation, the same time frame has to be used for all species.

Table A.3: Recruitment function coefficients.

Species		α_i	β_i	γ_i
Cod	Coefficient	0.382	$-1.32 \cdot 10^{-3}$	0.304
	SE	0.086	$2.78 \cdot 10^{-4}$	0.052
	p-value	0	0	0
Sprat	Coefficient	4.745	$-4.22 \cdot 10^{-4}$	NA
	SE	0.253	$2.35 \cdot 10^{-4}$	
	p-value	0.073	0	
Herring	Coefficient	3.574	$-6.74 \cdot 10^{-4}$	NA
	SE	0.134	$1.32 \cdot 10^{-4}$	
	p-value	0	0	

Note: based on 1974-2014 data. Source: ICES 2014.

Within the model, each species is subject to simultaneous fishing mortality (F), natural mortality (M) and, in the case of prey species, predation mortality (P). Thus, the development of the age classes $a \geq 2$ is given by:

$$x_{i,a+1,t+1} = \exp(-F_{i,a,t} - M) x_{i,a,t}, i \in (c); a \in [2,8] \quad (\text{A.5a})$$

$$x_{i,a+1,t+1} = \exp(-F_{i,a,t} - M - P_{i,a,t}) x_{i,a,t}, i \in (h, s); a \in [1,8]. \quad (\text{A.5b})$$

The last age category (age 8) is considered a reservoir for all adults of age ≥ 8 . The natural mortality from causes other than predation (M) is assumed constant and equal to 0.2 for all species (ICES, 2014). The predation is not constant, and for realistic results has to be set in the form of appropriate relationships when implementing predator-prey feedbacks (Gårdmark et al., 2013). Thus, the predation mortality of herring and sprat caused by cod is modeled in the form of functional responses (Heikinheimo, 2011). The rate is linearly related to the number of predators and dependent on the relative density of prey in the relevant age category and the diet preference coefficient derived from cod stomach content compositions. Thus, the number of fish of species $i \in (s, h)$ at age a eaten by cod population of age b in year t is given by:

$$p_{i,a,b,t} = \frac{x_{c,b,t} C_b \left(\sum_{i' \in (s,h)} \sum_{a'=1}^8 x_{i',a',t} \right)^n}{\left(\sum_{i' \in (s,h)} \sum_{a'=1}^8 x_{i',a',t} \right)^n + D_{sh}^n} \frac{\lambda_{i,a,b} x_{i,a,t}}{\sum_{i' \in (s,h)} \sum_{a'=1}^8 (\lambda_{i',a',a} x_{i',a',t})} \quad (\text{A.6})$$

where C_b is the maximum consumption of herring and sprat by one cod at age b , D_{sh} is the half saturation constant, estimated to be 260 billion individuals (Heikinheimo, 2011), n is the functional response constant, assumed to be equal 2 and $\lambda_{i,a,b}$ is the relative consumption preference of cod at age b over species i at age a derived according to stomach contents (Tomczak et al., 2012), as in Thøgersen et al. (2013). The preference coefficients are presented in Table A.5. The annual maximum consumption of pelagic species (C_b) was estimated at 30, 100 and 135 for cod at age one, two and older than two, respectively (Heikinheimo, 2011). The fishing mortalities are derived from the weight of total harvest of species i , H_i , by separating it into age categories as follows:

$$h_{i,a,t} = \frac{H_i \text{sel}_{i,a} x_{i,a,t}}{\sum_{a=1}^8 \text{sel}_{i,a} x_{i,a,t} w_{i,a}} \quad (\text{A.7})$$

where $\text{sel}_{i,a}$ is harvest selectivity coefficient for species i at age a and $h_{i,a,t}$ is harvest of species i of age a at time t in number of fish. This indicates that the distribution of harvest between age categories is density dependent with certain preferences revealed by the applied fishing techniques. Additionally, transforming the harvest to the model based on number of specimens requires dividing both sides by weight at age ($w_{i,a}$). The harvest of cod is assumed to have an additional impact on the stock; therefore, to arrive at realistic catch values, the landings were multiplied by discard multiplier ($d_{c,a}$) given for each age category. The fishing mortality for cod at age a and time t ($F_{c,a,t}$) was derived via solving a nonlinear function:

$$d_{c,a} h_{cat} = \frac{F_{c,a,t} x_{c,a,t} (1 - e^{-F_{c,a,t} - M})}{F_{c,a,t} + M} \quad (\text{A.8})$$

In the case of pelagic species that are subject to predation, deriving fishing mortality ($F_{i,a,t}$, $i \in (s,h)$) requires solving a system of two equations with predation mortality ($P_{i,a,t}$) as follows:

$$\begin{cases} h_{iat} = \frac{F_{i,a,t}x_{i,a,t}(1-e^{-F_{i,a,t}-P_{i,a,t}-M})}{F_{i,a,t}+P_{i,a,t}+M} \\ \sum_{b \in [1,8]} p_{i,a,b,t} = \frac{P_{i,a,t}x_{i,a,t}(1-e^{-F_{i,a,t}-P_{i,a,t}-M})}{F_{i,a,t}+P_{i,a,t}+M} \end{cases}, i \in (s, h). \quad (\text{A.9})$$

Selectivity coefficients and discard multipliers were derived for each age category OLS regression using 2008-2012 data (ICES, 2014) reflecting modern fishing tendencies, technological progress and conservation efforts (e.g., minimum mesh sizes) in recent years. The harvest parameters are presented in Table A.6.¹⁶

Table A.5: Cod diet preference coefficients

	Cod age 1	Cod age 2	Cod age ≥ 3
Sprat age 1	0.234	0.251	0.211
Sprat age ≥ 2	0.337	0.320	0.360
Herring age 1	0.246	0.271	0.211
Herring age 2	0.106	0.096	0.104
Herring age ≥ 3	0.077	0.061	0.113

Note: Values based on Tomczak et al. (2012) and Thøgersen et al. (2013).

Table A.6: Harvest parameters (2008-2013).

Age	1	2	3	4	5	6	7	≥ 8
Selectivity - cod	^a	0.072 (0.014)	0.325 (0.031)	0.297 (0.028)	0.355 (0.024)	0.331 (0.051)	0.280 (0.064)	0.270 (0.085)
Selectivity - sprat	0.085 (0.009)	0.170 (0.012)	0.209 (0.016)	0.231 (0.012)	0.247 (0.011)	0.261 (0.017)	0.221 (0.025)	0.227 (0.027)
Selectivity - herring	0.026 (0.004)	0.056 (0.006)	0.093 (0.007)	0.119 (0.011)	0.130 (0.011)	0.150 (0.017)	0.189 (0.018)	0.174 (0.015)
Discard multiplier - cod	^a	2.038 (0.190)	1.314 (0.057)	1.152 (0.021)	1.122 (0.026)	1.059 (0.027)	1.028 (0.022)	1.014 (0.016)

Note: based on 2008-2013 data (ICES, 2014); Standard errors in brackets; ^a no harvest activity in

¹⁶ The surprisingly decreasing selectivity coefficient for cod at age categories starting from 6 may be explained by old specimens being rare and the potential to exhibit different behavior patterns.

the given age category. Source: ICES, 2014.

Fish stocks described by the multispecies interaction model are also subject to commercial harvest by the existing fleet (limited entry regulations). The maximum harvest of cod, herring and sprat within the model is given as a single species TAC. The total catch allowance is derived according to harvest control rules (HCRs) based on target fishing mortality that follow regulations currently in place (Council Regulation (EC) No 1098/2007 for cod, CFP for herring and sprat). Under the current cod management plan, the goal in terms of F is equal to 0.3 for cod ages between 4 and 7. The HCR for pelagic species follows the single species maximum sustainable yield (MSY) with F values 0.29 for sprat (age 3-5) and 0.18 for herring (age 3-6). The TAC is set annually and therefore the management in place can be considered adaptive (Walters and Hilborn, 1978), as total catch is adjusted every year to meet the management plan target as close as possible. The risk of overfishing is reduced by setting limit reference points under which harvest is prohibited. The limit reference points are set by ICES and refer to the minimum spawning biomass, which permits a long-term sustainable exploitation of the stock. The levels below are considered to be possibly dangerous for the capacity of self-renewal of the stock (Caddy and Mahon, 1995). Those values are, in 1000 tones, 63 for cod, 430 for herring and 410 for sprat (ICES 2014).

Appendix B. Profit Maximization Process

Detailed data on harvest by the Polish fishing fleet is available through the Polish Fisheries Monitoring Centre in Gdynia, which is a branch of the Fisheries Department under the Ministry of Agriculture and Rural Development in Warsaw. It is confidential data originating from the vessel logbooks, and it contains detailed harvest volumes (fresh weight) of each species for each fishing trip performed in the Baltic Sea in the period 2008-2012 together with vessel

parameters. The effort was derived from the time the vessel spent at sea,¹⁷ i.e., from the time of leaving the port until return. The summary of the data used to estimate the distance function is presented in Table B1.

Table B1. Summary of the logbook data.

	Vessels ≥ 12 m		Vessels 8-11.99 m	
	Mean	SD	Mean	SD
Effort [h]	1754.6	945.1	826.1	695.6
Harvest of cod [t]	48.6	53.6	20.1	22.8
Harvest of herring [t]	128.8	301.2	6.4	18.3
Harvest of sprat [t]	375.7	850.1	0.0	0.3
Harvest of other species [t]	36.5	69.8	15.2	26.2
Power [kW]	249.7	133.2	62.6	31.6
Number of observations	847		757	
Number of units	287		273	
Number of units in 2012	189		222	

Source: Polish Fisheries Monitoring Centre.

Note: Due to the availability of data for the biological process, we adopt 411 (= 189 + 222) vessels for the simulation steps while whole data is adopted in the estimation of Equation (13).

The outputs include four groups of harvested species: cod (*c*), herring (*h*), sprat (*s*) and, assuming perfect substitution among other species, a linearly aggregated group of other fish (*o*). For the capital variable describing the vessel's size (*k*), the power of the main engine was chosen.¹⁸ The observations accounting for less than 24 h of effort per year were excluded as

¹⁷ Effort is a proxy variable for an unobservable composite variable input. Proxy variables may potentially lead to biased and inconsistent parameter estimates.

¹⁸ Power of the main engine is a proxy variable for an unobservable composite capital stock and may potentially lead to biased parameter estimates.

lacking character of commercial harvest. Data were divided into two length categories, as vessels below 12 m represent a different type of fishery with no sprat oriented harvest activity.¹⁹

The individual efficiencies are estimated according to equation (13) with data scaled by dividing each parameter by the population mean (Coelli & Perelman, 2000). The estimation results together with robust standard errors adjusted for clusters identified by observation for the same vessel over years are presented in Table B2.

Landing prices originate from the supplementary material of the 2015 Annual Economic Report on the EU Fishing Fleet available through the Scientific, Technical and Economic Committee for Fisheries (STECF) and are presented in Table B3. Derived values are based on the aggregated value of each fishery in 2013. Prices varying between length categories are assumed to reflect the quality of landed fish.

¹⁹ Note that the sprat quota redistribution coefficient for vessels below 12 m is 0 indicating that minimal amounts harvested is an incidental bycatch. In addition, vessels below 12 m harvest significantly less herring compared to larger units.

Table B2. Estimated distance function coefficients

	Vessels ≥ 12 m		Vessels 8-11.99m	
	Estimate	p-val	Estimate	p-val
α_c	0.162 (0.026)	***	0.311 (0.029)	***
α_h	0.164 (0.033)	***	0.017 (0.029)	
α_s	0.154 (0.034)	***		
α_o	0.109 (0.025)	***	0.115 (0.029)	***
α_k	-1.031 (0.464)	**	-0.098 (0.211)	
α_{cc}	0.042 (0.007)	***	0.058 (0.007)	***
α_{ch}	-0.004 (0.002)	*	-0.012 (0.003)	***
α_{cs}	-0.006 (0.003)	**		
α_{co}	-0.010 (0.002)	***	-0.041 (0.004)	***
α_{hh}	0.046 (0.008)	***	-0.001 (0.008)	
α_{hs}	-0.011 (0.003)	***		
α_{ho}	-0.009 (0.003)	***	-0.020 (0.003)	***
α_{ss}	0.051 (0.009)	***		
α_{so}	-0.011 (0.003)	***		
α_{oo}	0.026 (0.006)	***	0.042 (0.006)	***
α_{kk}	0.651 (0.934)		-0.049 (0.428)	
α_{kc}	-0.074 (0.017)	***	-0.018 (0.015)	
α_{kh}	-0.048 (0.028)	*	0.028 (0.016)	*
α_{ks}	0.014 (0.023)			
α_{ko}	-0.021 (0.025)		-0.025 (0.017)	
<hr/>				
Fixed Effects				
Individual	Yes		Yes	
Time	No		No	

Note: standard deviations in brackets; *** at 1%, ** at 5%, and * at 10% of significance level.

Table B3. Summary of the landing price data.

Vessel length	Cod	Herring	Sprat	Other
8 - 9.99 m	1.261	0.427	0.318	1.164
10 - 11.99 m	1.280	0.388	0.358	0.610
12 – 17.99 m	1.147	0.370	0.274	0.434
18 – 23.99 m	1.104	0.340	0.270	0.431
≥ 24 m	1.055	0.362	0.275	0.527

Note: All prices in 2013 Euro per kg of fresh weight. Source: STECF 2014.

The variable cost for vessels of a minimum of 12 m is based on unit cost per day at sea (24 h) available through 2010 sample of annual cost reports received from the Polish Marine Institute in Gdynia (Kuzebski E., personal communication) and derived as a function of capital as $c_v = 86.4 + 5.0k$ [2012 Euro]. The cost of vessels below 12 m is based on the STECF report (STECF 2013) and equals to 103.5 [2012 Euro] per day at sea. The variable costs include fuel expenditure, maintenance, gear, ice, and other variable costs, as well as crew wages. The fixed costs are calculated according to vessels size as $cf=91.3$ k [2012 EUR] for vessels over 12 m and as $cf=44.4$ k [2012 EUR] for vessels under 12m. The maximum number of days at sea indicates the maximum effort for a given size category within the model: 160 days for vessels over 12 m and 90 days for units between 8 and 12 m. The limitation for bigger vessels is associated with regulations (EC Regulation 1098/2007). Smaller vessels are highly limited by sea conditions, weather, etc. and therefore a lower number was used, equal to approximately 95th percentile of the effort distribution within the length category.

The TAC at time t is allocated between all eligible vessels in accordance with the

redistribution system currently in use (regulation 282/1653 from December 23, 2011 [in Polish]). The total allowance of species i ($TAC_{i,t}$) is divided among units according to the coefficient that in turn depends on the vessel size. The allocation system is summarized by the equation:

$$IVQ_{i,n,t} = \frac{z_{i,n}TAC_{i,t}}{\sum_{n \in N} z_{i,n}}, \quad (B1)$$

where $IVQ_{i,n,t}$ is individual quota of species i given to vessel n at time t and $z_{i,n}$ is the redistribution coefficient for species i , assigned to the vessel n according to its length. The model does not permit rollover allowances, and thus unused quotas in a given year are lost. Moreover, the model proceeds under full compliance with the given allocations.²⁰ The redistribution coefficients which individual quotas are based on equation 1 are presented in Table B4.

Table B4. TAC redistribution coefficients.

Vessel length	Cod	Herring	Sprat
8 - 9.99 m	0.40	0.4	0
10 - 11.99 m	0.69	0.4	0
12 - 14.99 m	0.86	0.4	0.2
15 - 18.49 m	1	0.6	0.4
18.5 - 20.49 m	0.97	1	1
20.5 - 25.49 m	0.97	2.0	2.0
25.5 - 30.49 m	0.97	4.0	3.5
30.5 m and over	0.27	4.0	4.0

Note: Based on Polish regulation in place (regulation 282/1653 from December 23, 2011 [in Polish]).

²⁰ National authorities under coordination by the European Fisheries Control Agency (EFCA) conduct the control over Illegal, Unreported and Unregulated (IUU) fishing (surveillance, inspections, data collection and enforcement). The enforcement legal basis is Council Regulation (EC) No 1224/2009.

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Figures

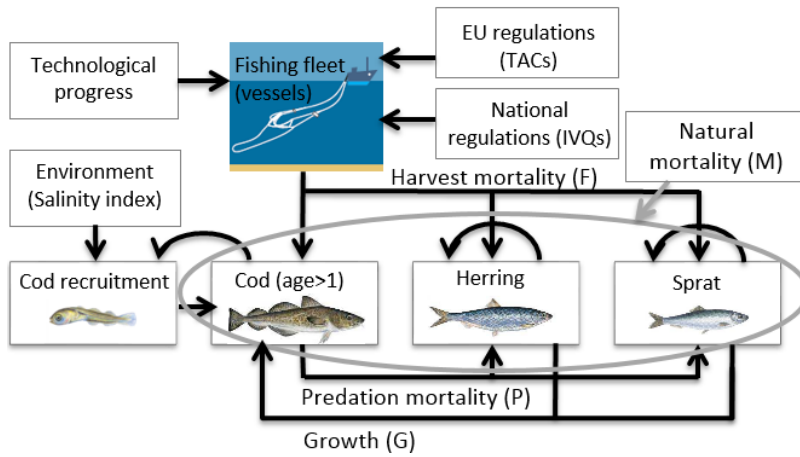


Figure 1. The Baltic Sea major interactions

Images: European Commission (2004)

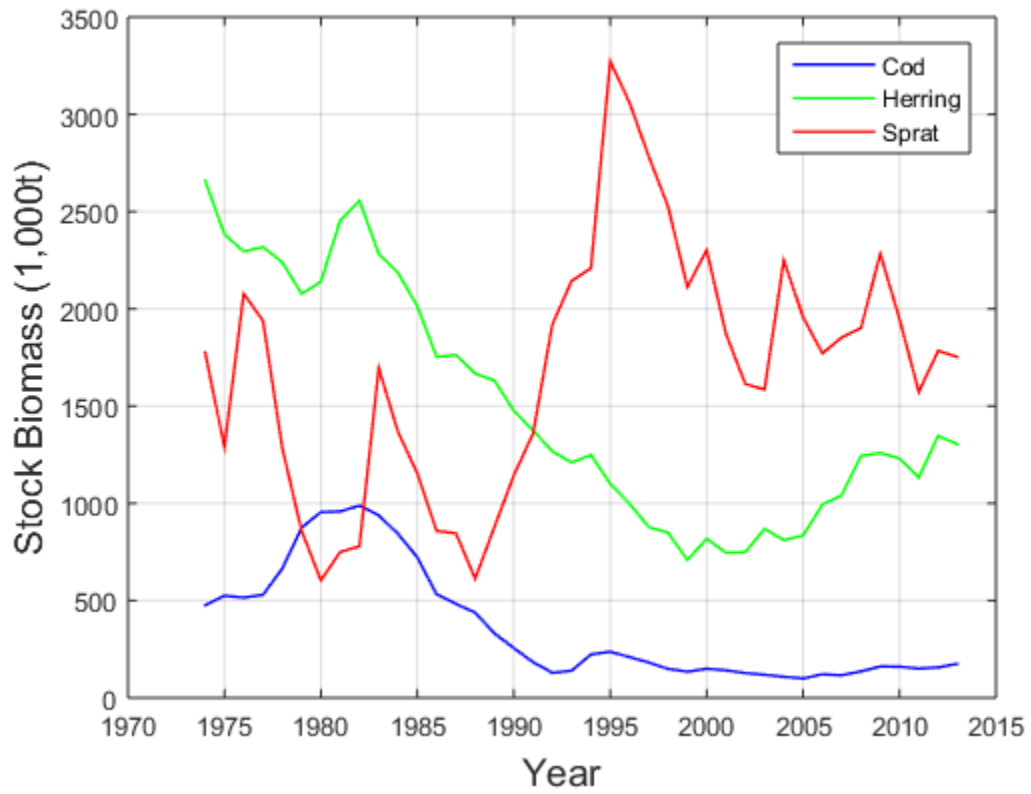


Figure 2. Historical fluctuation of the stock biomass

Note: The spawning stock biomass of this figure is in Fig. 1 of Hutniczak (2015, p. 204.)

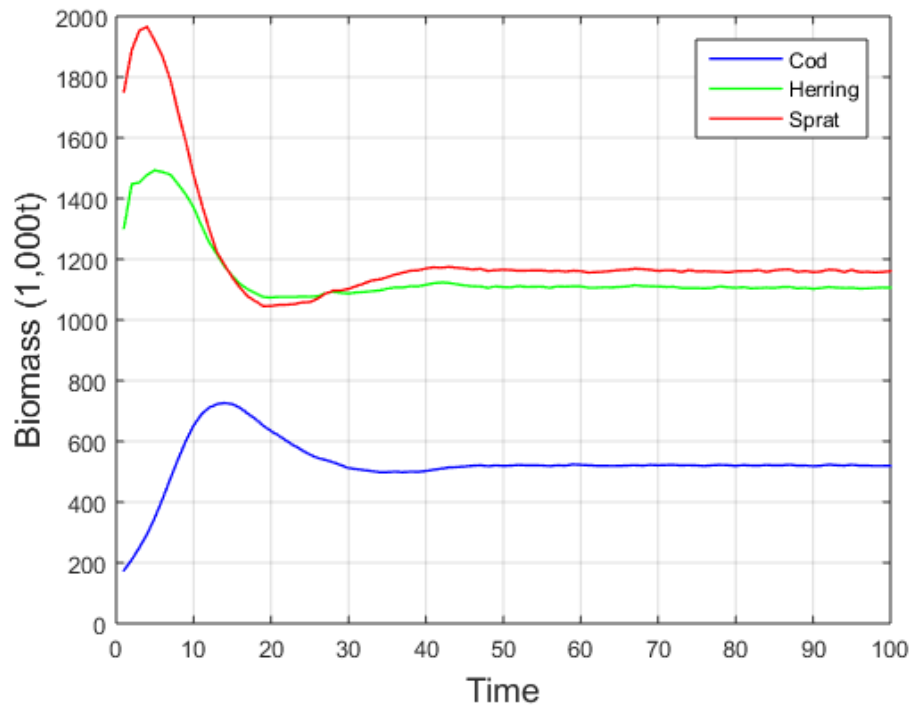


Figure 3. Time simulation for 100 years starting from 2012

Note: The steady state adopted in the analysis is the mean of each stocks from 51 to 100 years:
 $ss = [526.9322, 1142.8130, 1213.5266]$ (1,000 ton) for cod, herring and sprat.

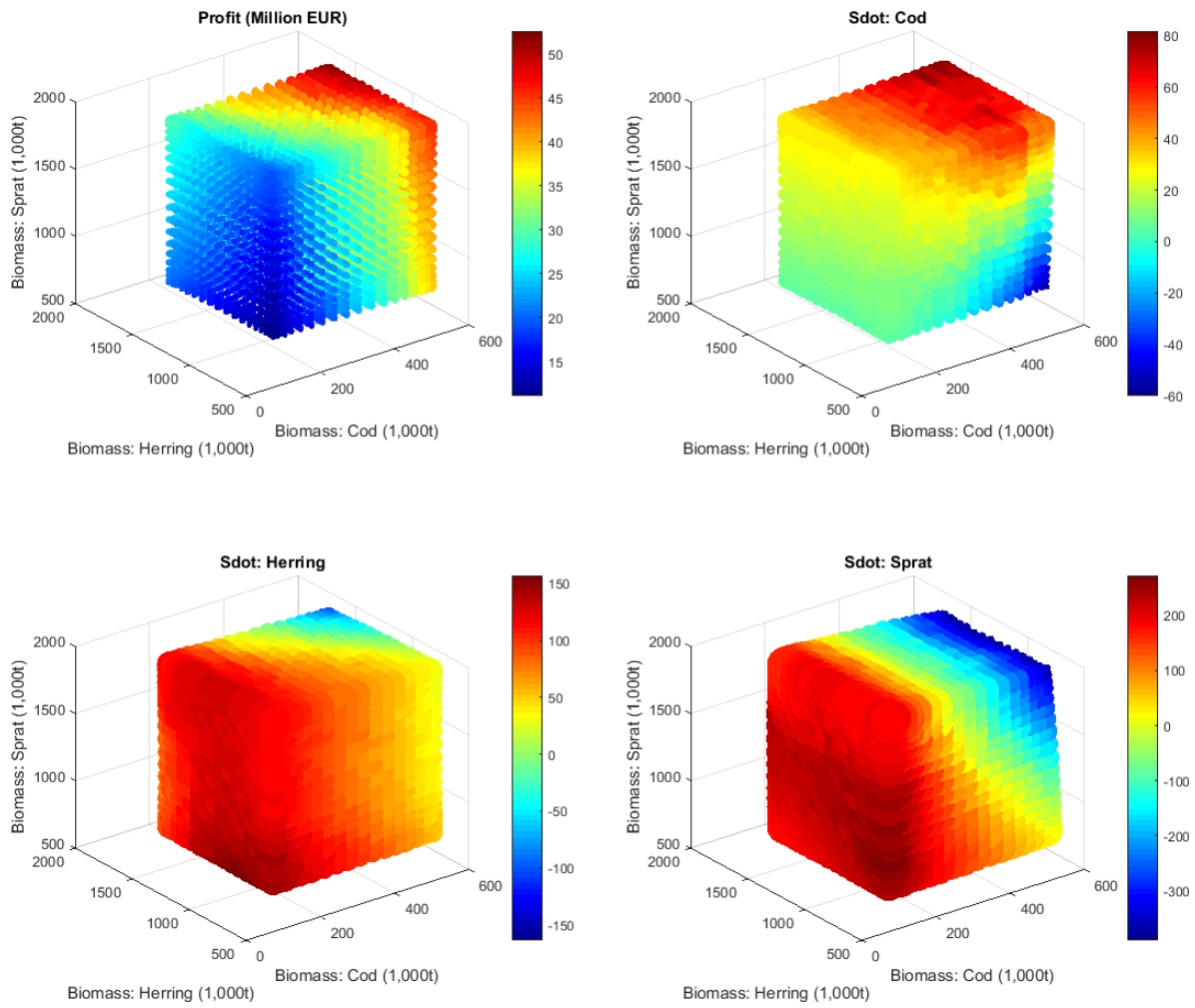


Figure 4. Data generation: simulated profit (W) and the growth rate (\dot{s}_i)

Note: The simulation is based on the [20 x 20 x 20] Chebyshev polynomial nodes from the lower bound = [130, 685.688, 728.116] and the upper bound = [560, 1,599.938, 1,941.643] for cod, herring and sprat.

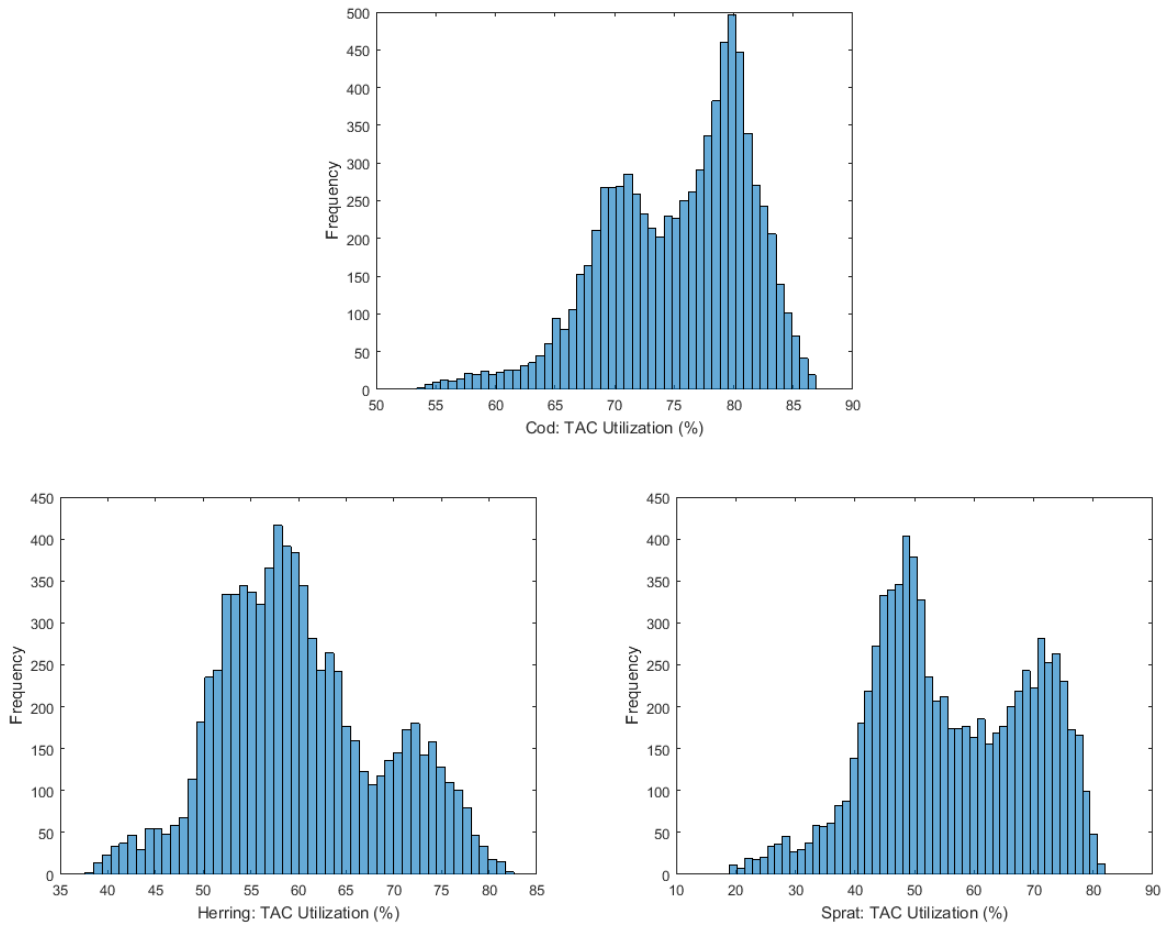


Figure 5. TAC Utilization

Note: The historical utilization was 68% ~ 99% for cod, 39% ~ 122% for herring, and 41% ~ 95% for sprat during year 2008 to year 2012 (details in Hutniczak (2015)).

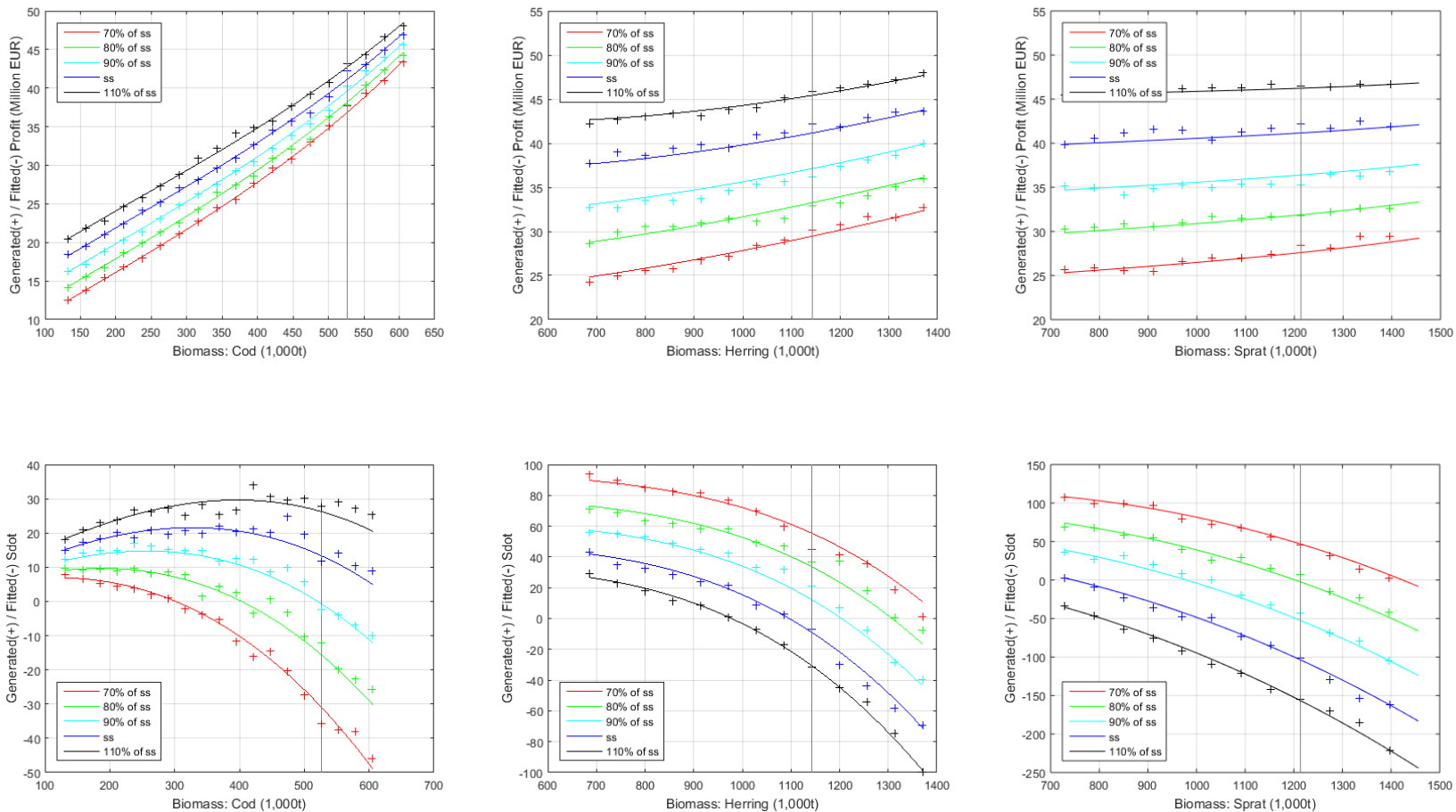


Figure 6. Generated and fitted curves

Note: The curve generated from [3 x 3 x 3] order polynomials. For the representation purpose, the fitting is performed through the evenly gridded 2,873 data nodes from 70% of and 110% of the steady state. The goodness of measures are the adjust R2 (0.9981, 0.9844, 0.9948, 0.9981) for profit and each of \dot{s}_i . In the natural capital valuation, all 8,000 Chebyshev nodes are applied.

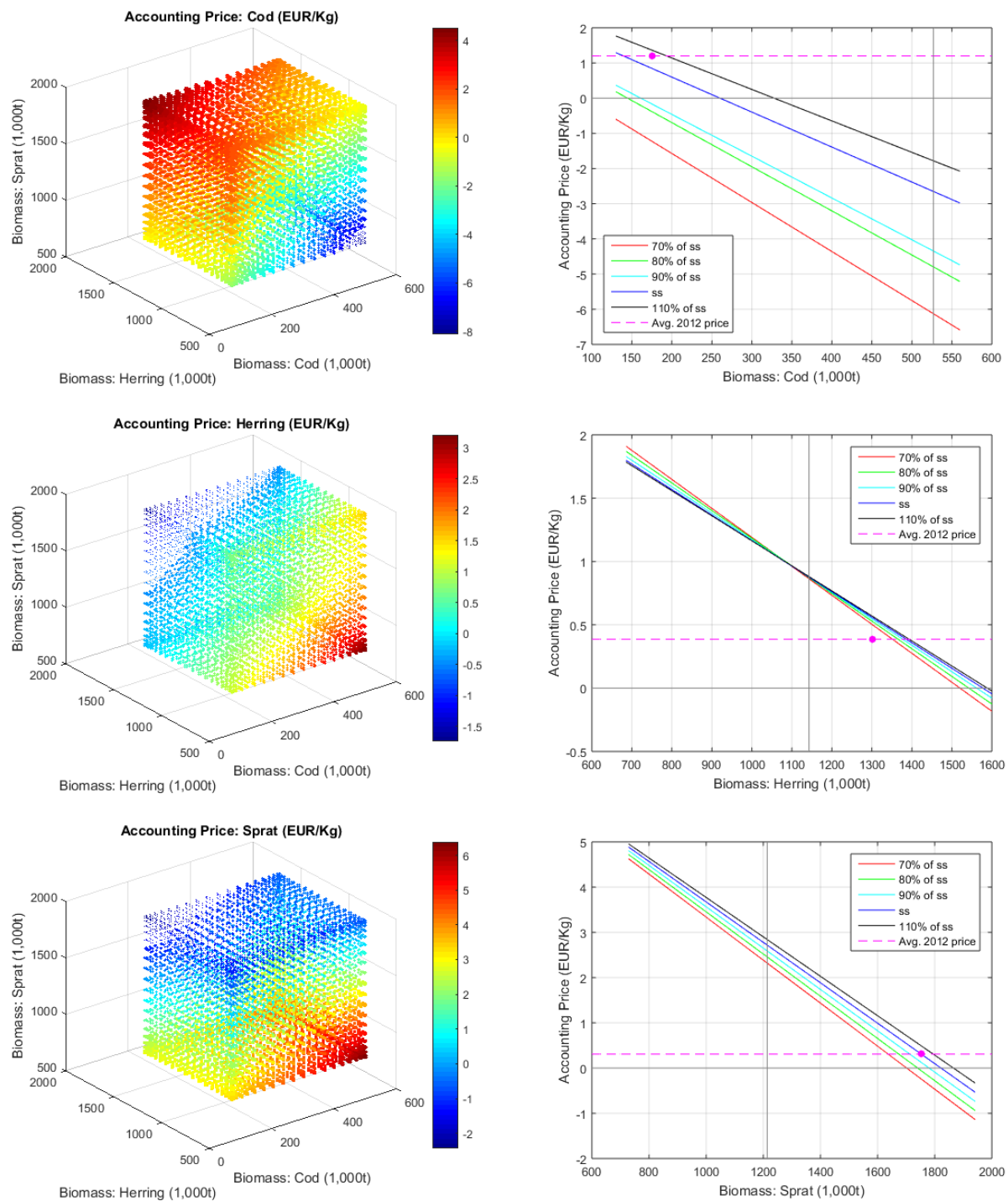


Figure 7. Accounting prices

Note: The last two columns are accounting prices when the other two species are fixed at the specified stock levels.

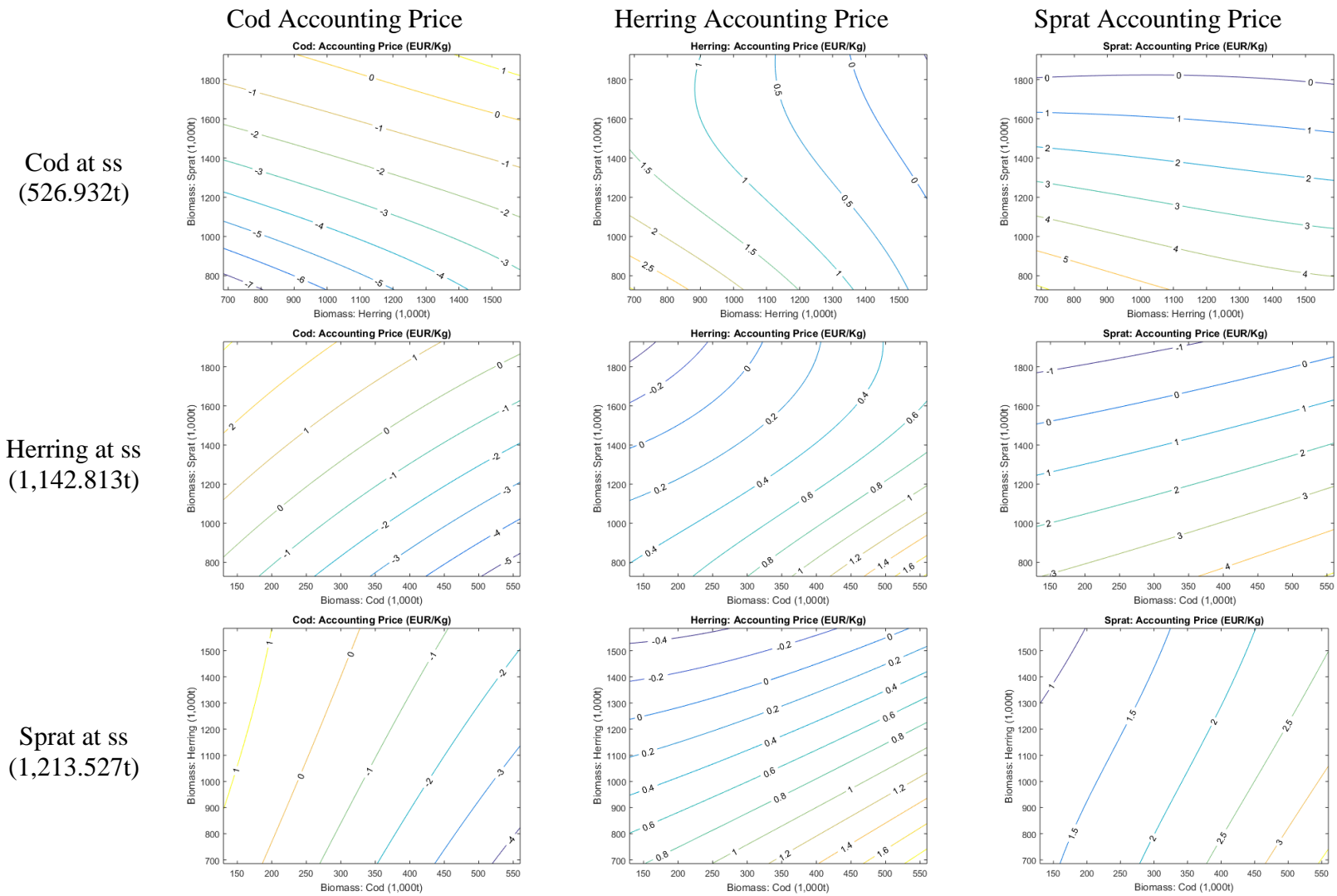


Figure 8. Contours of accounting prices

Note: The accounting prices are calculated by fixing each species of the first column.

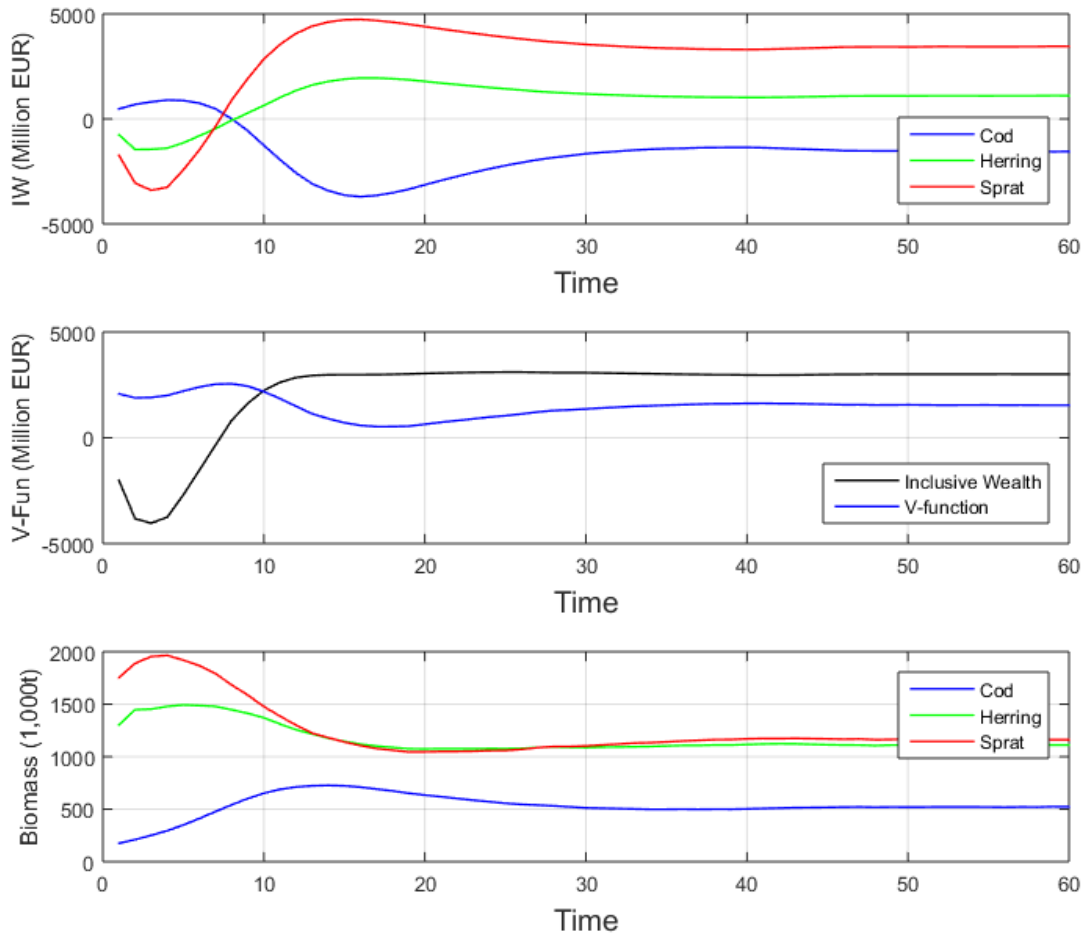


Figure 9. Time dynamics of inclusive wealth

Note: The bottom figure is cut by the first 60 years from Figure 3.

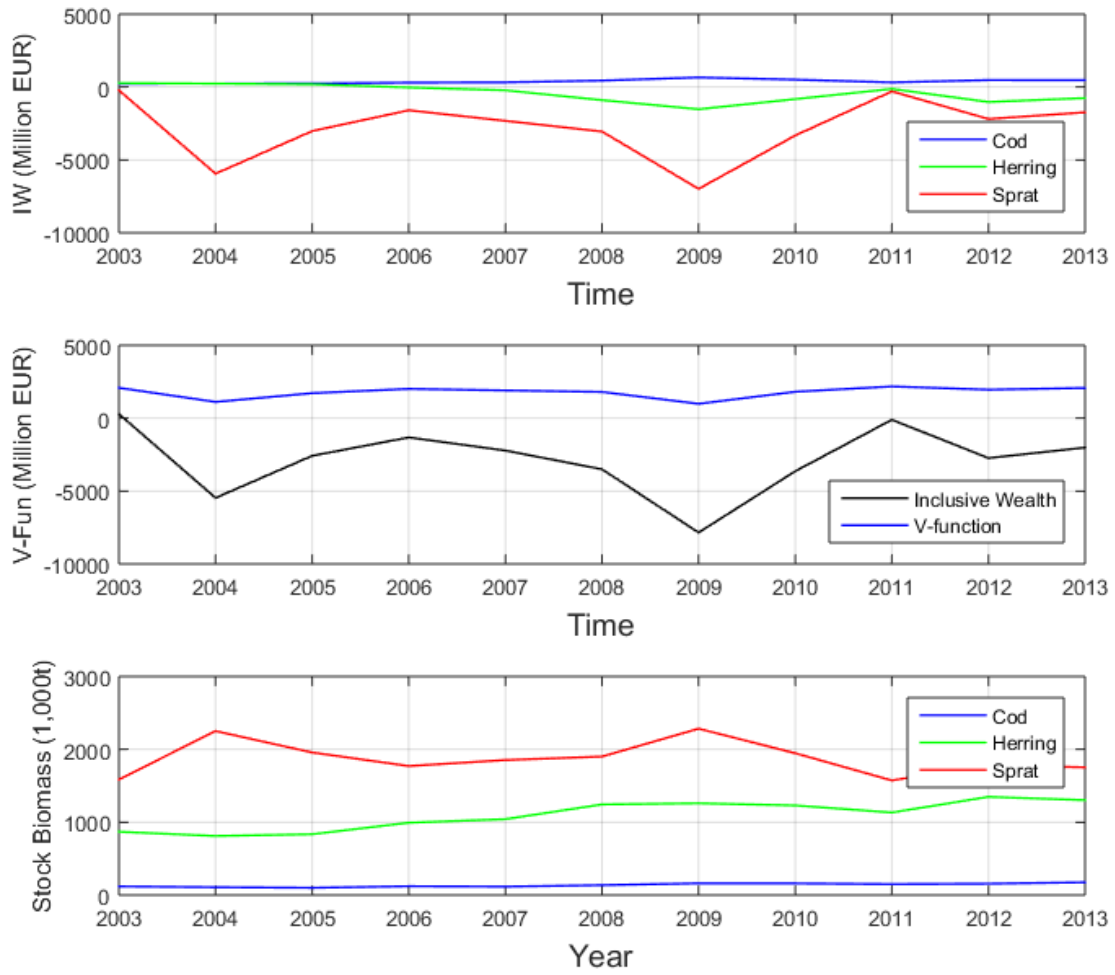


Figure 10. Time dynamics of inclusive wealth

Note: The values are calculated from the historic stock values in Figure 3.