Received: 27 June 2021 | Accepted: 13 February 2022

DOI: 10.1111/nrm.12341

Natural Resource Modeling WILEY

Joint management of marine mammals and a fish species: The case of cod and grey seals in the Nordic-Baltic Sea countries

Johan Blomquist[1] | **Frank Jensen**[2] | **Staffan Waldo**[1] | **Ola Flaaten**[3] | **Maija K. Holma**[4]

[1]Department of Economics, Swedish University of Agricultural Sciences, Lund, Sweden

[2]Department of Food and Resource Economics, University of Copenhagen, Copenhagen, Denmark

[3]University of Tromso (UiT), The Arctic University of Norway, Tromso, Norway

[4]Department of Economics and Management, University of Helsinki, Helsinki, Finland

Correspondence
Johan Blomquist, Swedish University of Agricultural Sciences, Department of Economics, Sceelevangen 15D, Lund 22002, Sweden.
Email: johan.blomquist@slu.se

Funding information
Nordisk Ministerråd, Grant/Award Number: (173)-2018-FiskOgSæl

Abstract

In this paper, we present a simple theoretical, steady-state equilibrium, predator-prey model for the joint management of marine mammals and a fish species. As an empirical case, we choose cod and grey seals in the Nordic-Baltic Sea countries, and several benefits and costs related to the latter are considered. We show that the optimal grey seal population is much lower than the actual population, and this result is robust to variations in relevant parameter values. This result can be explained by the fact that the profit from harvesting cod is much higher than the net benefits from grey seals.

Recommendations for Resource Managers

- Consider the implications of joint management of a fish species and grey seals.
- Consider benefits and costs related to grey seals.

- Consider the implications of benefits and costs related to grey seals for the harvest and population of grey seals in Nordic-Baltic Sea countries.
- Consider the implications of benefits and costs related to grey seals for the harvest and stock size of cod in Nordic-Baltic Sea countries.

KEYWORDS
cod, grey seals, joint management, Nordic-Baltic Sea Countries

1 | INTRODUCTION

At a global level, many marine mammal populations are currently recovering due to conservation efforts, but interactions with fish stocks frequently generate conflicts (see Magera et al., 2013) but many marine mammals generate important benefits and costs; therefore, joint management with fish species becomes important (see ICES, 2021). However, in practical policy, there are very few examples of the joint management of fish stocks and marine mammals (see FAO, 2008).[1] Fisheries and grey seals in the Nordic-Baltic Sea countries offer a good example of management issues related to fish stocks and marine mammals. The grey seal population in the Baltic Sea is currently recovering at a remarkably high speed. Specifically, due to successful conservation measures, the grey seal population has increased from approximately 4000 individuals in the 1970s to approximately 50,580 individuals in 2017.[2] Such an increase in the grey seal population may exert negative impacts on the Nordic-Baltic Sea countries due to seal-induced mortality of fish and damage costs related to the fishing industry and parasite infections (see Königson et al., 2009; Waldo et al., 2020; Sokolova et al., 2018). However, grey seals also represent a valuable resource due to activities such as tourism and recreational hunting (see Bosetti & Pearce, 2003). Furthermore, grey seals may be seen as a symbol of a healthy marine environment and are often perceived as an intelligent and clever species, implying that population control through harvesting may be perceived as unethical.

A strand of economic literature investigates human–wildlife conflicts between marine mammals and fish species. Flaaten (1988) analyzes the interaction between marine mammals and fish species in the Barents Sea in a model where fishermen are driven by profit maximization, while Flaaten and Stollery (1996) investigate the profit loss in the cod and herring fisheries in Norway associated with an increase in the population of minke whales. Adaptation strategies for salmon fisheries in Finland under various scenarios for the grey seal population by using calculated values of the current and future profits are identified in Holma et al. (2014), while Finnoff and Tschirhart (2003) analyze how the harvest of pollock in the northern Pacific depends on the population of stellar sea lions. Finally, Boncoeur et al. (2002) investigate how the optimal size of marine protected areas depends on the interaction between grey seals and fish species, while Jansson and Waldo (2022) investigate profits in the Swedish fisheries sector under different assumptions about the grey seal population. However, in this literature, there is no attempt to discuss the management implications of considering the benefits and costs related to marine mammals, and this constitutes an important research topic.

The purpose of this paper is to address this study gap by using cod and grey seals in Nordic-Baltic Sea countries as an empirical case. We consider the benefits of grey seal watching and recreational hunting and damage costs related to the fishing industry and parasitic infections. To focus on the implications of including these benefits and costs, we use a simple theoretical steady-state equilibrium predator-prey model with grey seals as predators and fish as prey species. The model is used to formulate several management scenarios for cod and grey seals in the Nordic-Baltic Sea countries, including optimal joint management and fixed grey seal populations. To parameterize the model, the benefits and costs related to grey seals are valued by using simple methods such as benefit transfer and direct calculations. By using the parametrized model, we are able to generate empirical results for various indicators for the Nordic-Baltic Sea countries, including the stock size, harvest and profit of cod and the population, harvest, and net benefit of grey seals.

Our paper is related to a reasonably large theoretical literature on predator-prey models (see Diz-Pita & Otero-Espinar, 2021 for a review). In this literature, dynamic adjustment paths for predator and prey populations are investigated, and it is common to use a Lotka-Volterra model (see Wagersky, 1978). Traditionally, this literature has focused on the direct impact of the population of one species on the population of the other species and this can be described as a top-down, predator-prey model (see Shi et al., 2017). Topics investigated with top-down, predator-prey models include extinction, global stability, and almost periodical solutions (see Ahmad & Stamova, 2005 and Xu & Chen, 2001). However, a number of recent papers have included feedback effects in theoretical predator-prey models (see Jiang & Lu, 2007). A feedback effect arises when the direct population effects influence another variable that then affects the population of the predator and prey species. In this paper, we contribute to the literature on theoretical predator-prey models by studying the empirical implications of considering the benefits and costs related to the predator; therefore, we restrict our attention to a top-down, predator-prey model.

The rest of the paper is structured as follows. In Section 2, we present a simple theoretical predator-prey model, while a number of management scenarios are described in Section 3. The parametrization of the model for cod and grey seals in the Nordic-Baltic Sea countries is discussed in Section 4, and Section 5 presents the empirical results. Section 6 contains a summary and discussion.

2 | THEORETICAL MODEL

The model in this paper is structured around four characteristics. First, in the empirical model, we investigate one predator represented by grey seals and one prey species represented by cod. However, the theoretical model is presented in a general way, and therefore, we utilizing the term fish species instead of cod. Second, we assume that the stock size of the fish species and the grey seal population are in a steady-state equilibrium where the change in the stock size or population between time periods is equal to zero. Thus, we do not discuss adjustment paths toward a steady-state equilibrium. The justification for focusing on a steady-state equilibrium is that we consider several benefits and costs related to grey seals, which implies that the dynamic adjustment paths toward an equilibrium may become very complicated. Third, we maximize what has been called the long-run economic yield, implying that we only consider the profit and net benefits for one time period and disregard discounting. Finally, the empirical model covers the Nordic-Baltic Sea countries, represented by Denmark, Sweden, and Finland, and we do not discuss the allocation of net benefits among the countries. Thus, we use terms such as the Baltic Sea and the Nordic-Baltic Sea countries.

In Table 1, we provide an overview of the components of the model and the associated assumptions.

TABLE 1 Summary of basic modeling assumptions

Equation	Species	Name	Function	Basic assumptions
Net benefit	Fish species	Price of fish	p_f	Constant price of a fish species.
		Cost of harvesting fish	$CC(h_f, x_f)$	Positive and nondecreasing marginal harvesting costs, negative marginal stock cost. $\left(\frac{\partial CC(h_f,x_f)}{\partial h_f} > 0,\ \frac{\partial^2 CC(h_f,x_f)}{\partial {h_f}^2} \geq 0,\ \text{and}\ \frac{\partial CC(h_f,x_f)}{\partial x_f} < 0\right)$
	Grey seals	Benefit of recreational grey seal hunting	$HB(h_S, x_S)$	Positive and nonincreasing marginal benefit of recreational grey seal hunting in both the harvest and population of grey seals. $\left(\frac{\partial HB(h_s,x_s)}{\partial x_s} > 0, \frac{\partial HB(h_s,x_s)}{\partial h_s} > 0, \frac{\partial^2 HB(h_s,x_s)}{\partial {h_s}^2} \leq 0,\ \text{and}\ \frac{\partial^2 HB(x_s)}{\partial {x_s}^2} \leq 0\right)$
		Benefit of grey seal watching	$WB(x_s)$	Positive and nonincreasing marginal benefits of grey seal watching in the grey seal population. $\left(\frac{\partial WB(x_s)}{\partial x_s} > 0\ \text{and}\ \frac{\partial^2 HB(x_s)}{\partial x_s^2} \leq 0\right)$
		Damage cost to the fishing industry	$ND(x_s)$	Positive and nondecreasing marginal damage costs to the fishing industry in the grey seal population. $\left(\frac{\partial ND(x_s)}{\partial x_s} \geq 0\ \text{and}\ \frac{\partial^2 ND(x_s)}{\partial x_s^2} \geq 0\right)$
		Damage cost of parasites	$PD(x_s)$	Positive and nondecreasing marginal damage costs of parasites in the grey seal population. $\left(\frac{\partial PD(x_s)}{\partial x_s} > 0 \text{ and } \frac{\partial^2 PD(x_s)}{\partial {x_s}^2} \geq 0\right)\frac{\partial PD(x_s)}{\partial x_s} > 0 \text{ and } \frac{\partial^2 PD(x_s)}{\partial {x_s}^2} \geq \left(\frac{\partial PD(xs)}{\partial x_s} > 0\ \text{and}\ \frac{\partial^2 PD(xs)}{\partial x_s^2} < 0\right)$
Resource restrictions	Fish species	Natural growth of fish	$F(x_f)$	Inverse u-shaped growth function. $\left(\frac{\partial F(x_f)}{\partial x_f} > 0\ \text{for}\ x_f < x_{f,MSY},\ \frac{\partial F(x_f)}{\partial x_f} \leq 0\ \text{for}\ x_f \geq x_{f,MSY}\ \text{and}\ \frac{\partial^2 F(x_f)}{\partial x_f^2} < 0\right)\frac{\partial F(x_f)}{\partial x_f} > 0\ x_f < x_{f,MSY}$ $\frac{\partial F(x_f)}{\partial x_f} \leq 0\ x_f \geq x_{f,MSY} \frac{\partial^2 F(x_f)}{\partial {x_f}^2} < 0$
		Seal-induced mortality of fish	$G(x_s)$	Positive and nondecreasing marginal mortality in the grey seal population.

TABLE 1 (Continued)

Equation	Species	Name	Function	Basic assumptions
				$\frac{\partial G(x_s)}{\partial x_s} > 0\ \frac{\partial^2 G(x_s)}{\partial {x_s}^2} \geq 0 \left(\frac{\partial G(x_s)}{\partial x_s} > 0 \text{ and } \frac{\partial^2 G(x_s)}{\partial x_s^2} \geq 0 \right)$
	Grey seals	Natural growth of grey seals	$H(x_s)$	Inverse u-shaped growth function. $\frac{\partial H(x_s)}{\partial x_s} > 0\ x_s < x_{s,MSY}\ \frac{\partial H(x_s)}{\partial x_s} \leq 0\ x_s \geq x_{s,MSY}$ $\frac{\partial^2 H(x_s)}{\partial {x_s}^2} < 0 \left(\frac{\partial H(xs)}{\partial x_s} > 0 \text{ for } x_s < x_{s,MSY},\ \frac{\partial H(x_s)}{\partial x_s} \leq 0 \text{ for } x_s \geq x_{s,MSY} \text{ and } \frac{\partial^2 H(x_s)}{\partial x_s^2} < 0 \right)$

The assumptions about the signs of the first- and second-order derivatives of the relevant functions in Table 1 are consistent with basic models in fisheries economics (see Conrad & Clark, 1987; Clark, 1990) and environmental economics (see Baumol & Oates; 1988; Hanley et al., 1997), and we do not discuss these below. However, we briefly introduce each benefit and cost function with the purpose of identifying resource restrictions (Section 2.1) and net benefit functions (Section 2.2).

2.1 | Resource restrictions

We first discuss the resource restrictions for the fish species. We let x_f be the stock size of a fish species in a steady-state, while x_s is the grey seal population in equilibrium. For the fish species, we operate with a natural growth function, and we assume that this function depends only on x_f (see Neher, 1990 for a justification). The natural growth function for the fish species is denoted $F(x_f)$. In addition, grey seals prey on the fish species; therefore, we include a seal-induced mortality function in the model. It is assumed that the seal-induced mortality function only depends on the grey seal population,[3] and this function is denoted by $G(x_s)$. Finally, h_f denotes the harvest of the fish species in equilibrium. Given these facts, the resource restriction for the fish species in a steady-state equilibrium becomes:

$$F(x_f) - G(x_s) - h_f = 0. \tag{1}$$

From (1), it is clear that for the fish species, the natural growth is equal to the seal-induced mortality plus the harvest in a steady-state equilibrium. Note that we have assumed that $F(x_f)$ and $G(x_s)$ are additively separable in the resource restriction, a common assumption in economic predator-prey models (see Getz, 1984). Note that interaction between the fish species and grey seals is captured with the seal-induced mortality of fish in our model.

Turning to the resource restriction for the predator, $H(x_s)$ captures the natural growth function of grey seals. The steady-state equilibrium harvest of grey seals is denoted by h_s and then the resource restriction for the predator becomes:[4]

$$H(x_s) - h_s = 0. \tag{2}$$

Thus, for grey seals, the natural growth is equal to the harvest in a steady-state equilibrium.

2.2 | Objective functions

To identify an objective function, we start with a discussion of the fish species. We assume that fish are harvested solely for commercial purposes, and p_f denotes a constant output price at a common market in Nordic-Baltic Sea countries (see Asche et al., 2007 for a discussion of the price on fish products). $CC(h_f, x_f)$ is the cost of harvesting the fish species in the Nordic-Baltic Sea countries,[5] and then the total profit, $NBF(h_f, x_f)$, becomes:

$$NBF(h_f, x_f) = p_f h_f - CC(h_f, x_f). \tag{3}$$

Turning to the predator, we include the benefit of recreational grey seal hunting in the model. Following Arnell and Southwick (2015), this benefit is assumed to depend on both the population and harvest of grey seals, and the benefit function is denoted by $HB(h_S, x_S)$. We also include a benefit of grey seal watching, which is assumed to depend on the population of the predator, and the benefit function is denoted by $WB(x_s)$. Grey seals also impose damage costs on the fishing industry. The damage costs related to the fishing industry are assumed to depend on the grey seal population[6] and are denoted as $ND(x_s)$. Grey seals also infect fish with parasites, which generates a damage cost. The damage costs of parasites are assumed to depend on the grey seal population, and $PD(x_s)$ covers this cost.[7] Given this notation, the net benefit of grey seals, $NBS_S(h_s, x_s)$, becomes:[8]

$$NBS(h_s, x_s) = HB(h_s, x_s) + WB(x_s) - ND(x_s) - PD(x_s). \tag{4}$$

Note that from (4), the net benefit of grey seals depends on both the population and harvest of the species.

3 | SCENARIOS

In this section, we formally describe various scenarios for the management of cod and grey seals in the Baltic Sea and these scenarios can be described by using the resource restrictions and objective functions from Sections 2.1 and 2.2. Table 2 provides an overview of the scenarios.

In Section 3.1, we describe scenario 1 (joint management), while Section 3.2 contains a characterization of scenarios 2–4 (fixed grey seal populations).

3.1 | Joint management

In scenario 1, we investigate joint management of cod and grey seals in the Baltic Sea. Thus, we maximize the total net benefits from cod and grey seals, $NBT(h_f, x_f, h_s, x_s)$, subject to the resource restrictions from (1) and (2). Formally, this problem can be written as:

$$\begin{aligned} &MaxNBT(h_f, x_f, h_s, x_s) = Max[NBF(h_f, x_f) + NBS(h_s, x_s)] = \\ &Max[p_f h_f - CC(h_f, x_f) + HB(h_s, x_s) + WB(x_s) - ND(x_s) - PD(x_s)] \end{aligned} \tag{5}$$

s.t.
(1), (2).

TABLE 2 Scenarios for the grey seal population in the Baltic Sea

Scenario number	Name	Description
1	Optimal joint management	Joint optimal management of grey seals and cod.
2	Fixed grey seal population, 10,000 individuals	The grey seal population is 10,000 individuals. The profit of harvesting cod is maximized.
3	Fixed grey seal population, zero	The grey seal population is zero. The profit of harvesting cod is maximized.
4	Fixed grey seal population, the carrying capacity.	The grey seal population is at the carrying capacity. The profit of harvesting cod is maximized.

Now the following Lagrange function can be set up:

$$L = p_f h_f - C(h_f, x_f) + HB(h_s, x_s) + WB(x_s) - ND(x_s) - PD(x_s) + \lambda(F(x_f) - G(x_s) - h_f) + \mu(H(x_s) - h_s), \tag{6}$$

where $\lambda > 0$ and $\mu > 0$ are Lagrange multipliers measuring the marginal user cost of the stock size of the cod and grey seal population, respectively. By using h_f and h_s as control variables and x_f and x_s as state variables, we obtain the following first-order conditions:[9]

$$\frac{\partial L}{\partial h_f} = p_f - \frac{\partial CC}{\partial h_f} - \lambda = 0, \tag{7}$$

$$\frac{\partial L}{\partial h_s} = \frac{\partial HB}{\partial h_s} - \mu = 0, \tag{8}$$

$$\frac{\partial L}{\partial x_f} = -\frac{\partial CC}{\partial x_f} + \lambda \frac{\partial F}{\partial x_f} = 0, \tag{9}$$

$$\frac{\partial L}{\partial x_s} = \frac{\partial HB}{\partial x_s} + \frac{\partial WB}{\partial x_s} - \frac{\partial ND}{\partial x_s} - \frac{\partial PD}{\partial x_s} - \lambda \frac{\partial G}{\partial x_s} + \mu \frac{\partial H}{\partial x_s} = 0. \tag{10}$$

The first-order conditions for the optimal harvest of cod and grey seals are given by (7) and (8). For cod, (7) implies that the marginal revenue (the price) is equal to the marginal social costs of the harvest. The marginal social cost of the harvest is equal to the marginal harvesting cost plus the marginal user cost of the stock size of cod. According to (8), the marginal social net benefits of harvesting grey seals is equal to zero. The marginal social benefits of harvesting grey seals are equal to the marginal benefit of recreational grey seal hunting minus the marginal user cost of the grey seal population. For the stock size of cod, (9) indicates that the marginal cost reduction due to an increase in the stock size is equal to the costs of the marginal growth. From (10), the optimal grey seal population occurs where the marginal net benefit (the marginal benefit of recreational grey seal hunting and watching minus the marginal damage costs related to the fishing industry and parasites) is equal to the cost of the marginal growth plus the value of the marginal seal-induced mortality of cod.

In total, (1), (2) and (7)–(10) represent six equations with six unknowns (h_f, h_s, x_f, x_s, λ, and μ), and this system can be solved to yield the optimal values of the unknown variables denoted by h_f^*, h_s^*, x_f^*, x_s^*, λ^*, and μ^*. By inserting optimal values of the harvest and stock size of cod and grey seals in (5), the optimal total net benefit of cod and grey seals under optimal joint management becomes $NBT^*(h_f^*, x_f^*, h_s^*, x_s^*)$. We can also find the optimal total harvesting profit ($NBF^*(h_f^*, x_f^*)$) and the optimal total net benefit from grey seals ($NBS^*(h_s^*, x_s^*)$). In this paper, we empirically calculate the value of these indicators.

3.2 | Fixed grey seal population

In scenarios 2–4, we analyze three targets for the grey seal population that are potential management objectives: (a) A minimum viable grey seal population; (b) A grey seal population at zero; and (c) A grey seal population at the carrying capacity. Now we discuss how these population targets can be investigated within our theoretical model and all three management objectives can be captured within the same framework.

The fixed grey seal population is denoted by $\bar{x}_s$, and to ensure consistency with scenario 1, we must ensure that the resource restriction in (2) is fulfilled. Thus, we must find a fixed steady-state equilibrium harvest of grey seals, $\bar{h}_s$, which is consistent with the fixed grey seal population, by using that $H(\bar{x}_s) = \bar{h}_s$. Then, we can insert $\bar{h}_s$ and $\bar{x}_s$ in the net benefit function for grey seals from (4) to obtain $\bar{N}BS(\bar{h}_s, \bar{x}_s)$, and since the harvest and population of grey seals are constants, the total net benefit for grey seals also becomes a constant. In the resource restriction for cod in (1), we can also use the fixed grey seal population to obtain:

$$F(x_f) - G(\bar{x}_s) - h_f = 0. \tag{11}$$

From (11), one implication of a fixed grey seal population is that the seal-induced mortality of cod becomes a constant.

Now the total net benefit of grey seals and cod from (5), with a constant net benefit of grey seals, can be maximized subject to (11), and to solve this problem, we can set up a Lagrange function. We let $\tau > 0$ be a Lagrange multiplier, and by using h_f as a control variable and x_f as a state variable, the first-order conditions become:

$$\frac{\partial L}{\partial h_f} = p_f - \frac{\partial CC}{\partial h_f} - \tau = 0, \tag{12}$$

$$\frac{\partial L}{\partial x_f} = -\frac{\partial CC}{\partial x_f} + \tau\frac{\partial F}{\partial x_f} = 0. \tag{13}$$

According to (12), the marginal revenue from harvesting cod (the price) is equal to the marginal social cost. From (13), the optimal stock size of cod occurs where the marginal cost reduction due to an increase in the stock size is equal to the cost of the marginal growth.

(11)–(13) represent three equations with three unknowns (h_f, x_f, and τ), and this system can be solved to yield optimal values for the unknowns, which we denote $\bar{h}_f, \bar{x}_f$, and $\bar{\tau}$, respectively. By using the optimal values of the harvest and stock size of cod in (3), we obtain the optimal total profit when the grey seal population is fixed, ($\overline{NBF}(\bar{h}_f, \bar{x}_f)$). Furthermore, since the total net benefit of grey seals is constant, the total net benefit of cod and grey seals is given by $\overline{NBT}(\bar{h}_f, \bar{x}_f, \bar{h}_s, \bar{x}_s) = \overline{NBF}(\bar{h}_f, \bar{x}_f) + \overline{NBS}(\bar{h}_s, \bar{x}_s)$. In this paper, we identify $\overline{NBF}(\bar{h}_f, \bar{x}_f)$, $\overline{NBS}(\bar{h}_s, \bar{x}_s)$, and $\bar{N}BT(\bar{h}_f, \bar{x}_f, \bar{h}_s, \bar{x}_s)$ empirically.

However, in scenarios 2–4, we have three different fixed grey seal populations. In scenario 2, the grey seal population is set at the minimum viable level as defined in the EU Habitats Directive for a good environmental status (see European Union, 1992). According to SwAM (2018), this population-level is 10,000 individuals, which is also recommended by HELCOM (2006), who provides regional guidelines for grey seal management in the Baltic Sea. The population target in scenario 2 can be treated in the theoretical model from above without any modifications.

Scenario 3 captures the situation in which the grey seal population is equal to zero, which implies no harvest of grey seals. Thus, we obtain that the total net benefit of grey seals is equal to zero ($\overline{NBS}(0, 0) = 0$). Furthermore, we assume that the seal-induced mortality of cod is zero when the grey seal population is zero; thus $G(0) = 0$. In scenario 3, we use these facts in (11)–(13).

In scenario 4, the grey seal population is set at the carrying capacity. This target can be justified by the current management regime, where such a grey seal population is recommended by HELCOM (2006). Within our model, a grey seal population at carrying capacity can be found from the growth function for the species. However, a population at the carrying capacity implies that the harvest of grey seals is zero; thus, the net benefits of grey seals become $\overline{NBS}(0, \bar{x}_S)$. We use these facts when solving (11)–(13) in scenario 4.

3.3 | Costs of nonoptimal joint management

From our model, optimal joint management generates an economic gain to Nordic-Baltic Sea countries compared with scenarios 2–4, but the size of this gain depends on the target for the grey seal population. We, therefore, calculate the cost of nonoptimal joint management as a function of the grey seal population, which can be defined as:

$$F = NBT^*(h_f^*, x_f^*, h_s^*, x_s^*) - \overline{NBT}(\bar{h}_f, \bar{x}_f, \bar{h}_s, \bar{x}_s). \tag{14}$$

In this paper, we calculate F for various values of the fixed grey seal population and, consequently, the harvest.

4 | FUNCTIONAL FORMS AND PARAMETER ESTIMATES

To quantify the outcome under the scenarios in Table 2, we must specify functional forms and estimate parameter values for the relations included in the theoretical model from Sections 2.1 and 2.2. Table 3 contains an overview of the assumed functional forms and parameter values.

Below, we describe only very briefly the assumed functional forms illustrated in Table 3. However, we verbally describe the parameterization of each function for cod and grey seals in the Baltic Sea in Sections 4.1–4.9, while details can be found in Supplementary Appendix A. The parameter values are summarized in Table 3 and include a benchmark value and upper and lower bounds. The benchmark value is the result obtained from estimation of each parameter, while the upper and lower bounds are created due to uncertainty about the estimated parameter. In Supplementary Appendix A, we discuss sources of uncertainty for each parameter value, but the upper and lower bounds are created by varying the benchmark value by ±50%.[10] Note also that some of our parameter values can be validated by comparison with the results from other studies, and this comparison can also be found in Supplementary Appendix A. Finally, when necessary, we use an official exchange rate to convert all monetary values into Euro, and we deflate all monetary measures to 2014 values by using a Danish Consumer Price Index from Statistics Denmark (available at https://www.dst.dk/en/).

4.1 | Natural growth of cod

Now we discuss how a natural growth function for cod in the Baltic Sea was estimated. From Table 3, it is clear that we assume a conventional logistic specification, where r_f is the intrinsic growth rate and K_f is the carrying capacity. To estimate this growth function, we use time series data on the stock size[11] and harvest of cod in the Baltic Sea for the period between 1988 and 2018, and based on these data, we can calculate time series for natural growth. Then, the

TABLE 3 Functional forms and parameter estimates for cod and grey seals in the Baltic Sea

						Parameter values		
Species	**Name**	**Functional forms**	**Parameter label**	**Method**	**Measurement unit**	**Benchmark level**	**Lower bound**	**Upper bound**
Cod	Price of cod	p_f	p_f: Price of cod.	Calculation	Euro/kilo	1.14	0.57	1.71
	Natural growth of cod	$F(x_f) = r_f x_f - \frac{r_f {x_f}^2}{K_f}$	r_f: Intrinsic growth rate for cod	Statistical estimation	Rate of change	1.699	0.8495	2.5485
			K_f: Carrying capacity for cod	Statistical estimation	Tons	244,039	122,020	366,059
	Seal-induced mortality of cod	$G(x_s) = g_s {x_s}^2$	g_s: Seal-induced mortality parameter for cod	Calculation	$1/(\text{tons})^2$	0.00015	0.000075	0.000225
	Cost of harvesting of cod	$CC(h_f, x_f) = \frac{cch_f^2}{x_f}$	cc: Cost parameter for harvesting cod	Statistical estimation	1000 Euro/tons	3.108	1.554	4.662
Grey seals	Natural growth of grey seals	$H(x_s) = r_s x_s - \frac{r_s {x_s}^2}{K_s}$	r_s: Intrinsic growth rate for grey seals	Statistical estimation	Rate of change	0.234	0.117	0.351
			K_s: Carrying capacity for grey seals	Statistical estimation	Tons	6551	3276	9826
	Benefit of recreational grey seal hunting	$HB(h_S, x_S) = hb_s \sqrt{x_S} \sqrt{h_S}$	hb_s: Benefit parameter for recreational grey seal hunting.	Benefit transfer	Euro/tons	0.1048	0.0524	0.1572
	Benefit of grey seal watching	$WB(x_s) = wb_s \sqrt{x_S}$	wb_s: Benefit parameter for grey seal watching	Benefit transfer	$\text{Euro}/(\text{tons})^{0.5}$	57.79	28.90	86.69
		$ND(x_s) = nd_s {x_s}^2$			$\text{Euro}/(\text{tons})^2$	0.000066	0.000033	0.000099

(Continues)

TABLE 3 (Continued)

						Parameter values		
Species	**Name**	**Functional forms**	**Parameter label**	**Method**	**Measurement unit**	**Benchmark level**	**Lower bound**	**Upper bound**
	Damage cost to fishing industry		nd_s: Damage cost parameter for fishing industry	Benefit transfer				
	Damage cost of parasites	$PD(x_s) = pd_s x_s^2$	pd_s: Damage cost parameter for parasites	Calculation	Euro/(tons)^2	0.00058	0.00029	0.00087

observations for natural growth and stock size can be directly used to estimate a logistic growth function by using ordinary least squares (OLS). This estimation procedure is labeled the ordinary approach. However, one potential problem with the ordinary approach is endogeneity of the estimated logistic growth function (see Ekerhovd & Gordon, 2013; Gordon, 2015). Specifically, the stock sizes on the right-hand side of a logistic growth function depend on the harvest if this variable is used in stock assessments. Furthermore, the harvest is also used to calculate the observations for natural growth on the left-hand side of the growth function. Thus, an endogeneity problem may arise, implying that the ordinary approach may generate biased estimators. An instrument variable (IV) approach may solve this problem. However, several different methodologies exist for obtaining stock estimates, and endogeneity is only a problem if the harvest is used in the stock assessments. The stock assessment for cod in the Baltic is based on a stock synthesis approach where both harvest data and harvest-independent data from scientific surveys are used. To investigate whether endogeneity arises with the ordinary approach, we use information from scientific surveys to undertake an IV regression of the logistic growth function. The results with the IV approach show that endogeneity is a minor problem for cod in the Baltic Sea. Specifically, the difference between the parameter values with the ordinary and IV approaches is very small (approximately 2% for both r_f and K_f). This difference is within the upper and lower bounds for the intrinsic growth rate and carrying capacity reported in Table 3; therefore, it is reasonable to use the parameter estimates generated with the ordinary approach in our paper.

4.2 | Natural growth of grey seals

As indicated in Table 3, we also assume a logistic growth function for grey seals, where r_s is the intrinsic growth rate and K_s is the carrying capacity. To estimate a logistic growth function, we use data for the population and harvest of grey seals in the Baltic Sea for the period between 2003 and 2017 to calculate a time series for natural growth. By using the observations for the natural growth and grey seal population, we can then estimate a logistic growth function by using the ordinary approach described in Section 4.1. To do so, we use OLS, but compared with cod, an additional problem is that the population and harvest of grey seals is measured by the number of individuals. To ensure consistency with the measurement unit for cod, we have therefore convert the population and harvest of grey seals into weight; here, we use the average weight of one grey seal in the Baltic Sea.[12] Note that the population is measured by counting the number of grey seals. Thus, the stock assessment is independent of the harvest of grey seals, which implies that the endogeneity issue described in Section 4.1 is a minor problem for grey seals.

4.3 | Seal-induced mortality of cod

Following Jost et al. (1999), we assume a quadratic seal-induced mortality function, where g_s is a mortality parameter for cod (see Table 3). However, we do not have sufficient information for estimating the mortality parameter with statistical methods; therefore, we follow Vestergaard (1996) and use one observation for total mortality and the grey seal population to calculate g_s. To obtain a measure for the total seal-induced mortality of cod in the Baltic Sea, we use information from Hansson et al. (2018). Specifically, for grey seals, we have data on the population, the total consumption of fish, and the share of cod in the diet of an average individual for 2013, and this information can be used to calculate one observation for the total seal-induced mortality for cod. For the grey seal population, we use the observation for 2013 from the time series described in Section 4.2. Thus, we are able to calculate the seal-induced mortality parameter for cod, but from Table 3, it is clear that the parameter is low, which implies that the interaction between cod and grey seals is small within our model.

4.4 | Price of cod

We assume that the price of cod is constant and independent of the harvest. To measure the price, we use landing prices received by Swedish vessels for cod harvested in the Baltic Sea for the period between 2008 and 2016. The average of these observations is our measure for the price.

4.5 | Cost of harvesting cod

We adopt a formulation of an industry cost function where the stock size of cod is included. The specific formulation, which can be found in Table 3, was used by Arnason et al. (2004), and *cc* is a cost parameter for harvesting cod in the Baltic Sea. Note first that the harvest of cod is a private good, while the stock size of cod is a public good, which is common for all Nordic-Baltic Sea countries. This fact implies that we cannot estimate cost functions that include both the stock size and harvest for each country separately and then aggregate these relations. Thus, we must aggregate the total cost and harvest observations for the Nordic-Baltic Sea countries and then estimate a common cost function. Another issue is that we do not have cost observations for Finland; therefore, we chose to use the total industry costs for Swedish vessels harvesting cod in the Baltic Sea. Then, we upscale these costs to cover all three countries by using aggregated national harvest shares for cod in the Baltic Sea. Note that we have access to cost observations for Denmark, but nonetheless, the total costs for Danish vessels are found by upscaling the costs for Sweden to ensure consistency with the cost observations for Finland. To ensure consistency with the cost observations, we also measure the harvest of cod by vessels from Finland and Denmark by upscaling observations for Swedish vessels. Finally, as mentioned in Section 4.1, we have information about the stock size of cod in the Baltic Sea. Thus, we have all necessary information to estimate the industry total cost function for harvesting cod in the Baltic Sea countries reported in Table 3 by using OLS. We use a method that is similar to the ordinary estimation approach described in Sections 4.1 and 4.2. Note that even though the harvest and stock size enter on the right-hand side of the cost function as independent variables, endogeneity is a minor problem since the costs are measured by using surveys among Swedish vessels.

4.6 | Benefit of grey seal watching

Following Trapper (2006), we operate with a benefit function where the square root of the grey seal population enters and, as indicated in Table 3, wb_s denotes the benefit parameter for grey seal watching. Again, we must use one observation for the total benefit of grey seal watching and the grey seal population to calculate the benefit parameter. To measure the total benefit of grey seal watching, we use Bosetti and Pearce (2003) and conduct a benefit transfer. An introduction to benefit transfer is provided by Westra and Boutwell (2013), but the basic idea is to transfer a monetary measure from a study site to a policy site; we undertake what has been labeled an uncorrected benefit transfer (see Johnston et al., 2015). To identify the willingness-to-pay (WTP) for grey seal watching per tourist per day in southwestern England in 1999 (the study site), Bosetti and Pearce (2003) use contingent valuation. Bosetti and Pearce (2003) also report the capacity per day of grey seal tourism in southwestern England, and thus we can calculate a WTP per day for grey seal watching. Next, we assume that grey seal watching occurs during a given number of days per year, implying that we can calculate the total benefit of grey seal watching. Bosetti and Pearce (2003) also report the number of grey seals in southwestern England, and we can use the average weight of one grey seal in the Baltic Sea to arrive at a measure for the grey seal population in weight. Thus, we are able to calculate wb_s.

4.7 | Benefit of recreational grey seal hunting

Following Fedler and Ditton (2001), we assume a benefit function of grey seal hunting where the square root of the population and harvest enters, and as indicated in Table 5, the benefit parameter is denoted by wb_s. To find this parameter, we must also use one observation for the total benefit of recreational grey seal hunting, the grey seal population, and the harvest of grey seals. In calculating the total benefit, we obtained access to data generated in a survey conducted by the Finnish Wildlife Agency about recreational grey seal hunting in Finland. We undertake an uncorrected benefit transfer since a monetary value for Finland (the study site) is transferred to all Nordic-Baltic Sea countries (the policy site). In the Finnish survey, the respondents reported the costs of one recreational grey seal hunting trip in 2017. Next, we assume that one grey seal is killed per recreational hunting trip, and this assumption is roughly confirmed in the Finish data set. By using the number of harvested grey seals described in Section 4.2, we can then obtain a measure for the total cost of recreational grey seal hunting. Next, we assume that the total benefit is equal to the total costs, and this condition holds under open-access in recreational grey seal hunting. Open-access is a common assumption in the literature on recreational hunting (see Gren et al., 2018). Thus, the total cost of recreational hunting becomes an approximation of the total benefit, and from Section 4.2, we also have information about the population and harvest of grey seals; therefore, we are able to calculate the benefit parameter of recreational hunting.

4.8 | Damage cost to the fishing industry

Here, we assume a quadratic damage cost function, which is commonly used in the environmental economic literature (see Hanley et al., 1997). From Table 3, nd_s denotes a damage cost parameter for the fishing industry, and again, we must use one observation for the total damage costs and grey seal population to calculate the parameter. To find the total damage cost to the fishing industry, we use Waldo et al. (2020), who measures the total damage costs to the Swedish fishing industry caused by grey seals. We undertake an uncorrected benefit transfer since a monetary measure for Sweden (the study site) is transferred to all Nordic-Baltic Sea countries (the policy site). The damage costs in Waldo et al. (2020) consist of three components:

(a) costs of damaged gear; (b) costs of increased working time; and (c) value of lost catches. The damage costs in Waldo et al. (2020) are from 2013 to 2014, and we take an average of these cost observations. However, Waldo et al. (2020) identify the total loss to the Swedish fishing industry and do not explicitly distinguish between fish species, but we obtained access to the data set behind the study. From the data set, we can derive the total damage cost for cod, but another problem is that Waldo et al. (2020) only identify damage costs for the Swedish fishing industry. Thus, as in Section 4.5, we must upscale the damage costs for Sweden to cover all Nordic-Baltic Sea countries by using the national harvest shares. Regarding the grey seal population, we use an average of the observations for 2013 and 2014 described in Section 4.2. Thus, we can calculate the damage cost parameter for cod in the Baltic Sea.

4.9 | Damage cost of parasites

To ensure consistency with the damage cost function for the fishing industry, we also assume a quadratic damage cost function of parasites, and pd_s is a damage cost parameter (see Table 3). Again, we must use one observation for the total damage costs and population of grey seals to calculate pd_s. Sokolova et al. (2018) investigate the spatial pattern of grey seal-related liver worms in cod in the Baltic Sea, Skagerak and Kattegatt in 2016 and 2017, and find that the conditions of the heavily infected Baltic Sea cod were approximately 15% lower than in uninfected fish. In this paper, we use this result and assume that 15% of the biomass of cod is lost due to parasitic infections. By using observations of the stock size of cod described in Section 4.1, we can measure the loss in the biomass of cod due to parasitic infections. Next, we can value this biomass loss; here, we use the price of cod discussed in Section 4.4.[13] This approach generates a measure for the total damage cost related to parasites, and from Section 4.2, we also have relevant information about the grey seal population; therefore, we can calculate the damage cost parameter.

5 | RESULTS[14]

In Section 5.1, we describe the results for scenarios 1–4 when using benchmark parameter values,[15] while Section 5.2 contains a summary of the sensitivity analysis. The loss of non-optimal joint management is discussed in Section 5.3. Note that we include observations for the actual stock size and harvest of cod and the actual population and harvest of grey seals as a part of the results.[16] These values are used for comparison with the results in scenarios 1–4, and we report observations from 2017.[17]

5.1 | Benchmark values

The results for scenarios 1–4 when using benchmark values for the parameters are summarized in Table 4.

From Table 4, we obtain three main results under joint management. First, the optimal grey seal population is much lower than the actual population, while the optimal harvest of grey seals is larger than the actual harvest. Second, the actual stock size and harvest of cod are much lower than the optimal stock size and harvest. Third, under joint management, the total profit

TABLE 4 Results for joint management and fixed grey seal populations (scenarios 1–4)

Indicator	Indicator	Measurement unit	Scenario 1 Joint management	Scenario 2 Fixed grey seal population, 10,000 individuals	Scenario 3 Fixed grey seal population, zero individuals	Scenario 4 Fixed grey seal population, Carrying capacity	Actual case
Net benefits	Total net benefits of grey seals and cod	1000 Euro	24,090	23,950	22,837	−644	
	Profit of harvesting cod	1000 Euro	22,831	22,823	22,837	22,402	
	Net benefits of grey seals	1000 Euro	1259	1127	0	−23,046	
Harvest	Cod	Tons	37,792	37,778	37,804	37,001	34,586
	Grey seals	Individuals	1381	1910	0	0	434
Population	Cod	Tons	219,221	219,147	219,283	215,163	108,656
	Grey seals	Individuals	6736	10,000	0	54,592	50,580

from harvesting cod is high compared with the total net benefits from grey seals, and the high profit implies that the total net benefit of joint management of grey seals and cod is reasonably high.

Turning to fixed grey seal populations (scenarios 2–4), these have a large effect on the net benefits of grey seals, as indicated in Table 4. Indeed, when the grey seal population is set at the carrying capacity (scenario 4), the total net benefit of the predator becomes a large negative number. The explanation for this result is the large damage costs related to the fishing industry (2,800,000 Euro) and parasitic infections (24,900,000 Euro) in scenario 4. However, compared with joint management, a fixed grey seal population has almost no effect on the stock size, harvest, and profit of cod (see Table 4). The explanation for this result is a low interaction between cod and grey seals (see Section 4.3).

5.2 | Sensitivity analyses

Next, we report the results of the sensitivity analysis under joint management. Here, we set one parameter value at the upper or lower bound while keeping the other parameters at the benchmark value (see Table 3). We use the sensitivity analyses to investigate the robustness of our results from Section 5.1,[3] and Table 5 reports the results obtained when varying the parameters in the resource restrictions.

From Table 5, varying the carrying capacity and intrinsic growth rate for cod has a large effect on the stock size and harvest of this species. Furthermore, varying the carrying capacity for cod has a large effect on the total net benefits of cod and grey seals, while varying the intrinsic growth rate has only a minor effect on the total net benefits (see Table 5). Compared with cod, varying the carrying capacity and intrinsic growth rate for grey seals has only a minor effect on the population and harvest of this marine mammal. Furthermore, varying the seal-induced mortality parameter has only a minor influence on all indicators and as in Section 5.1, the explanation for this result is the low interaction between cod and grey seals within our model. The low interaction also implies that varying the intrinsic growth rate for cod has only a minor influence on the population and harvest of grey seals, and a similar result is obtained for cod when varying the intrinsic growth rate for grey seals. We may also consider the robustness of our results for the grey seal population. From Section 5.1, we have that the optimal grey seal population is below the actual population, and from Table 5, this result is robust to variations in the parameters in the resource restrictions.

Table 6 summarizes the results obtained when varying the parameters in the profit function for cod and net benefit function for grey seals.

Table 6 shows that varying the price and harvesting cost parameter for cod has a large effect on the stock size and harvest of this species. Furthermore, varying the benefit parameters related to grey seal watching and recreational hunting has a reasonably large effect on the population and harvest of this marine mammal (see Table 6). However, since the total net benefit of grey seals is low (see Table 4), the effect of varying the benefit parameters for grey seals on the total net benefits of cod and grey seals is small. For the damage cost parameters related to the fishing industry and parasites, we achieve similar results. Furthermore, since the interaction between cod and grey seals is small within our model, varying the price and harvesting cost parameter of cod has almost no effect on the population and harvest of grey seals, and varying the relevant parameters for grey seals has almost no effect on the stock size

TABLE 5 Sensitivity analysis for the parameters in the resource restrictions joint management

Species	Parameter	Indicator	Measurement unit	Lower bound	Benchmark value	Upper bound
Cod	Carrying capacity	Stock size, cod	Tons	109,580	219,221	328,759
		Harvest, cod	Tons	18,890	37,792	56,835
		Population, grey seal	Individuals	6736	6736	6736
		Harvest, grey seals	Individuals	1381	1381	1381
		Total net benefits	1000 Euro	12,671	24,090	35,509
	Intrinsic growth rate	Stock size, cod	Tons	198,125	219,221	227,122
		Harvest, cod	Tons	31,581	37,792	40,040
		Population, grey seal	Individuals	6656	6736	6760
		Harvest, grey seals	Individuals	1367	1381	1385
		Total net benefits	1000 Euro	21,612	24,090	24,063
	Seal-induced mortality	Stock size, cod	Tons	219,252	219,221	219,191
		Harvest, cod	Tons	37,798	37,792	37,786
		Population, grey seal	Individuals	6771	6736	6702
		Harvest, grey seals	Individuals	1387	1381	1375
		Total net benefits	1000 Euro	24,093	24,090	24,087
Grey seals	Carrying capacity	Stock size, cod	Tons	219,222	219,221	219,221
		Harvest, cod	Tons	37,792	37,792	37,792
		Population, grey seal	Individuals	6705	6736	6746
		Harvest, grey seals	Individuals	1183	1381	1447
		Total net benefits	1000 Euro	24,087	24,090	24,091
	Intrinsic growth rates	Stock size, cod	Tons	219,222	219,221	219,220

(Continues)

TABLE 5 (Continued)

Species	Parameter	Indicator	Measurement unit	Lower bound	Benchmark value	Upper bound
		Harvest, cod	Tons	37,792	37,792	37,792
		Population, grey seal	Individuals	6681	6736	6778
		Harvest, grey seals	Individuals	685	1381	2082
		Total net benefits	1000 Euro	24,079	24,090	24,099

TABLE 6 Sensitivity analysis for the parameters in the profit function and net benefit function, joint management

Species	Parameter	Indicator	Measurement unit	Lower bound	Benchmark value	Upper bound
Cod	Price	Stock size, cod	Tons	231,188	219,221	208,192
		Harvest, cod	Tons	20,593	37,792	51,878
		Population, grey seal	Individuals	6789	6736	6644
		Harvest, grey seals	Individuals	1390	1381	1365
		Total net benefits	1000 Euro	7925	24,090	49,786
	Harvesting cost	Stock size, cod	Tons	198,188	219,221	227,102
		Harvest, cod	Tons	63,188	37,792	26,680
		Population, grey seal	Individuals	6656	6736	6760
		Harvest, grey seals	Individuals	1367	1381	1385
		Total net benefits	1000 Euro	41,981	24,090	17,060
Grey seals	Benefit of grey seal watching	Stock size, cod	Tons	219,257	219,221	219,179
		Harvest, cod	Tons	37,799	37,792	37,784
		Population, grey seal	Individuals	4324	6736	8759
		Harvest, grey seals	Individuals	931	1381	1719
		Total net benefits	1000 Euro	23,344	24,090	24,972
	Benefit of recreational grey seal hunting	Stock size, cod	Tons	219,223	219,221	219,219
		Harvest, cod	Tons	37,792	37,792	37,792
		Population, grey seal	Individuals	6642	6736	6830
		Harvest, grey seals	Individuals	1364	1381	1397
		Total net benefits	1000 Euro	24,071	24,090	24,109
	Damage cost to the fishing industry	Stock size, cod	Tons	219,217	219,221	219,225

(Continues)

TABLE 6 (Continued)

Species	Parameter	Indicator	Measurement unit	Lower bound	Benchmark value	Upper bound
		Harvest, cod	Tons	37,791	37,792	37,793
		Population, grey seal	Individuals	6974	6736	6517
		Harvest, grey seals	Individuals	1342	1381	1422
		Total net benefits	1000 Euro	24,112	24,090	24,069
	Damage cost of parasites	Stock size, cod	Tons	219,148	219,221	219,245
		Harvest, cod	Tons	37,778	37,792	37,797
		Population, grey seal	Individuals	9973	6736	5265
		Harvest, grey seals	Individuals	1906	1381	1112
		Total net benefits	1000 Euro	24,367	24,090	23,945

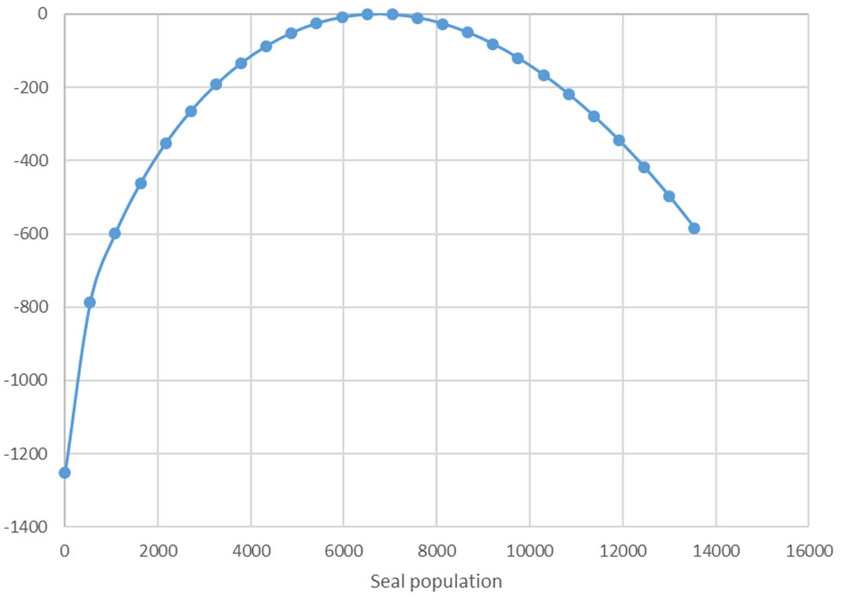

FIGURE 1 The total cost of nonoptimal joint management, 1000 Euro

and harvest of cod. Finally, from Table 6, it is clear that the actual grey seal population is higher than the optimal population for all parameter variations.

5.3 | Costs of nonoptimal joint management

Finally, we report the results for the cost of deviating from joint management by varying the grey seal population as described in (14). Figure 1 shows the total loss in the net benefits, while the slope of the curve can be interpreted as the marginal loss.

From Figure 1, we see that the numerical value of the marginal cost increases as we deviate from the optimal grey seal population. Regarding the total loss from nonoptimal joint management, we obtain a reasonably small total loss (less than 400,000 Euro) when the derivation of the grey seal population from the optimal level is low (less than 3500 individuals).

6 | SUMMARY AND DISCUSSION

The purpose of this paper is to investigate joint management of marine mammals and a fish species when including several benefits and costs related to the former. As an empirical case, we use cod and grey seals in the Baltic Sea, and we incorporate the benefits of recreational hunting and grey seal watching, as well as damage costs related to the fishing industry and parasitic infections caused by grey seals. For cod and grey seals in the Baltic Sea, we identify various management scenarios, including optimal joint management (scenario 1) and various fixed grey seal populations (scenarios 2–4). In scenario 1, we show that the optimal grey seal population is much lower than the actual population, while the optimal harvest is larger than the actual harvest. Furthermore, the actual stock size and harvest of cod are lower than the optimal values. In scenarios 2–4, fixed grey seal populations have a large effect on the total net benefit of the predator when the population is high. However, compared with joint management, fixed grey seal populations have only a minor effect on the stock size, harvest, and profit of cod. When parameterizing the model for the Baltic Sea, the benefits and costs related to grey seals are valued by using simple methods such as direct calculations and uncorrected benefit transfer, implying that many of our parameter values are highly uncertain. Therefore, we conduct sensitivity analyses by varying each parameter estimate separately by ±50%, and we are able to show that our empirical results are to a large extent robust to variations in the parameter values.

To focus on the benefits and costs related to grey seals, we make at least five simplifying assumptions, and it is useful to discuss the implications of relaxing these. First, in our model, the resource restriction for grey seals is independent of the stock size of cod. However, it can be argued that the resource restriction for grey seals should include a function that captures the addition to the grey seal population caused by cod. To examine this issue, we consider joint management and assume that the addition to the grey seal population only depends on the stock size of cod. Here it seems reasonable to assume that the marginal addition is positive and nonincreasing in the stock size of cod. Thus, the addition to the grey seal population becomes a benefit related to cod; therefore, the optimal stock size of cod tends to increase. The addition to the grey seal population arguably also depends on $x_{s,}$ but it seems reasonable to assume that this effect is captured in the carrying capacity in a logistic growth function. Despite this fact, including an addition to the grey seal population may potentially influence our results.

Second, we assume that the damage costs related to the fishing industry and parasites depend only on the grey seal population. However, it seems reasonable to assume that the stock size of cod also affects these damage costs. To discuss this issue, we consider joint management and assume that the marginal damage costs are positive and nondecreasing in the stock size of cod. Then, an additional marginal cost arises for the stock size of cod, and this tends to imply a decrease in x_f. Assume further that interaction between cod and grey seals occurs such that the marginal damage costs of the grey seal population are nondecreasing when the stock size of cod increases. Then, the grey seal population tends to decrease; therefore, when including the stock size of cod in the damage costs, both x_f and x_s tend to decrease.

Third, we assume that the seal-induced mortality of fish depends only on the grey seal population but normally the stock size of cod affects the mortality. To address this issue we consider joint management and assume that the marginal seal-induced mortality function is positive and nondecreasing in the stock size of cod, implying that x_f tends to decrease. Next, we assume interaction between cod and grey seals in the sense that the marginal seal-induced mortality function is nondecreasing in x_f. Then, the grey seal population also tends to decrease when including the stock size of cod in the mortality function. Thus, including the stock size of cod in the mortality function potentially affects our results.

Fourth, we present a steady-state equilibrium predator-prey model in which the long-run economic yield from cod and grey seals is maximized. As always in resource economics, it seems more relevant to use a dynamic model where adjustment paths toward a steady-state equilibrium are considered. However, according to Diz-Pita and Otero-Espinar (2021), the following problems may arise in conventional dynamic, predator-prey models: (a) An adjustment path toward a steady-state equilibrium may not exist; (b) An adjustment path toward a steady-state equilibrium may not be unique; and (c) An adjustment path toward a steady-state equilibrium can be sensitive to parameters and starting values. Compared with traditional predator-prey models, we include benefits and costs related to grey seals in our model;

therefore, it seems reasonable to postulate that the abovementioned problems is larger in our paper than in traditional predator-prey models. This provides a justification for using a static model as we do in this paper.

Finally, although we consider several benefits and costs related to grey seals, we nonetheless exclude relevant monetary values. As an example, grey seals are a symbol of a healthy marine environment since they were close to extinction in the Baltic Sea in the 1970s. Furthermore, many people are opposed to population control through hunting since grey seals are perceived as being intelligent and clever. These facts indicate that an existence value can be important and including such a benefit will tend to increase the optimal grey seal population.

ACKNOWLEDGMENT

The authors gratefully acknowledge funding from the Nordic Council of Ministers (grant number (173)-2018-FiskOgSæl).

AUTHOR CONTRIBUTIONS

Frank Jensen: methodology (lead); writing—original draft (lead). **Johan Blomquist**: methodology (lead); Writing—original draft (lead). **Staffan Waldo**: Project administration (lead); Writing—review & editing (equal). **Ola Flaaten**: Conceptualization (equal); Writing—review & editing (equal). **Maija K. Holma**: Conceptualization (equal); Writing—review & editing (equal).

DATA AVAILABILITY STATEMENT

Data openly available in a public repository that issues datasets with DOIs

ORCID

Frank Jensen http://orcid.org/0000-0002-7802-0517

ENDNOTES

[1] Two exceptions are Norway and Australia, where comprehensive joint management plans for fish species and marine mammals have existed for several decades (see Melding til Stortinget, 2020; Goldsworthy et al., 2019).

[2] The grey seal population in 2017 can be obtained by using the number of counted seals from HELCOM (2018).

[3] In theoretical predator-prey models, it is common to assume that the predator-induced mortality of the prey species depends on the stock size of both the predator and prey (see Getz, 1984). However, as a simplification, we assume that the seal-induced mortality of fish only depends on the grey seal population.

[4] In theoretical predator-prey models, it is common to include an increase in the grey seal population caused by the fish species in (2). However, as mentioned by Jost et al. (1999), it is useful to exclude this effect in empirical models to avoid double counting since $G(x_s)$ is included in (1). We chose to follow this advice in this paper.

[5] Since the stock size of the fish species is included in the cost function, we assume that harvesting cod occurs in a search fishery (see Neher, 1990). Significant marginal stock costs have been found for cod in many empirical papers (see Arnason et al., 2004).

[6] It can be argued that the damage costs to the fishing industry should depend on both the grey seal population and the stock size of fish. However, for simplicity we assume that the damage costs to the fishing industry only depend on the grey seal population.

[7] The fact that the damage cost of parasites depends on the grey seal population is confirmed in Beddington (1975), Haarder et al. (2014), and Lunneryd et al. (2015). However, it can be argued that the stock size of fish also affects the damage costs of parasite. Nonetheless, for simplicity, the stock size of fish is disregarded in the damage cost function related to parasites.

[8] Even though $ND(x_s)$ and $PD(x_s)$ capture fisheries-related costs, they are included in the net benefit function for grey seals because they depend on the grey seal population.

[9] We assume an interior solution for the control and state variables.

[10] A common way for identifying upper and lower bounds is to vary the benchmark value with ± 1.96 times the standard error. However, for many of our parameters, we cannot identify a standard error; therefore, we vary all estimated parameter with $\pm 50\%$.

[11] Note that the stock size of cod is measured by using the spawning stock biomass and not the total biomass.

[12] Thus, we have constructed a biomass model. However, an alternative is to use an age-structured model; examples can be found in Tahvonen (2008), Tahvonen et al. (2013), Diekert et al. (2010), and Skonhoft et al. (2012). Nonetheless, biomass models are easier to apply than age-structured models; so as a simplification, we restrict attention to the former.

[13] Parasitic infections mainly affect the quality of fish meat and, therefore, the price. However, we value the biomass loss related to parasites by using the market price and this yields the same results as when fish quality affects the price.

[14] Note that we convert the population and harvest of grey seals back into individuals by using the average weight of one grey seal in the Baltic Sea since this is the common way to express these variables for marine mammals. Note also that the measurement units for the parameter values in Table 3 differ, but when generating results, we ensure that all parameter values are measured in the same units.

[15] We performed several checks of our solution Four sets of simulations using different starting values are conducted to verify that the solutions are independent of the initial values. In addition, two different MATLAB solvers for nonlinear equations (fsolve and lsqnonlin) are applied to verify that the solutions represent a maximum. We have also confirmed that the resource restrictions in (1) and (2) are fulfilled and we determined that interior solutions for our control and state variables yield a higher net benefit than corner solutions in all relevant cases.

[16] The actual profit of cod and net benefits of grey seals could also have been reported. However, irrespective if we use the actual harvest of cod and grey seals or calculate a steady-state harvest of cod and grey seals by using the stock size of cod and population of grey seals, we obtain a large negative profit and net benefit. The explanation for this result is that the assumed functional forms summarized in Table 3 imply that our model has a limited scope for the control and state variables for which it can be used.

[17] We could have used observations for 2014 since we deflate all monetary measures to values from this year. However, we use observations for 2017 since there is a reasonably large decrease in the harvest and natural growth of cod between 2014 and 2017; and we want to use the most recent observations.

[18] Thus, we focus on the size of the effect of varying a parameter value. An alternative is to discuss numerical comparative static results and therefore focusing on the sign of the effect of varying a parameter value. The numerical comparative static results are reported in Supplementary Appendix B and all results are in line with the expectations.

REFERENCES

Ahmad, S., & Stamova, M. (2005). Partial persistence and extinction in N-dimensional competitive systems. *Applied Mathematical Computer Science*, *274*, 119–124.

Arnason, R., Sandal, L. K., Steinshamn, S. I., & Vestergaard, N. (2004). Optimal feedback controls: Comparative evaluation of the cod and herring fisheries in Denmark, Iceland, and Norway. *American Journal of Agricultural Economics*, *86*, 531–542.

Arnell, E. B., & Southwick, R. (2015). Economic and social benefits of hunting in North America. *International Journal of Environmental Studies*, *72*, 734–745.

Asche, F., Bjørndal, T., & Gordon, D. V. (2007). Studies in the demand structure for fish and seafood products. *Handbook of Operations Research in Natural Resources*, *33*, 295–314.

Baumol, W. J., & Oates, W. E. (1988). *The theory of environmental policy*. Cambridge University Press.

Beddington, J. M. (1975). Mutual interference between parasites or predators and its effect on searching efficiency. *Journal of Animal Ecology*, *44*, 331–346.

Boncoeur, J., Alban, F., Guyader, O., & Thébaud, O. (2002). Fish, fishers, seals and tourists: economic consequences of creating a marine reserve in a multi-species, multi-activity context. *Natural Resource Modeling*, *15*, 387–411.

Bosetti, V., & Pearce, D. W. (2003). A study of environmental conflict: the economic value of grey seals in Southwest England. *Biodiversity and Conservation*, *13*, 2361–2392.

Clark, C. W. (1990). *Mathematical bioeconomics. The optimal management of renewable resources*. Wiley-Interscience.

Conrad, J. M., & Clark, C. W. (1987). *Natural resource economics. Notes and problems*. Cambridge University Press.

Diekert, F., Hjarnason, D., Nævdahl, E., & Stenseth, R. (2010). Non-cooperative exploitation of multi-cohort fisheries—The role of gear selectivity in the North-East Arctic Cod Fishery. *Resource and Energy Economics*, *32*, 78–92.

Diz-Pita, E., & Otero-Espinar, M. V. (2021). Predator-prey models: A review of some recent advances. *Mathematics*, *9*, 1–34.

Ekerhovd, N. A., & Gordon, D. V. (2013). Catch, stock elasticity, and an implicit index of fishing effort. *Marine Resource Economics*, *28*, 379–395.

European Union. (1992). The Council Directive 92/43/EEC on the Conservation of Natural Habitats and of Wild Fauna and Flora. Official Journal of the European Communities No. L 206/7, Brussels.

FAO. (2008). *Human Dimensions of the Ecosystem Approach to Fisheries. An Overview of Context, Concepts, Tools and Methods* (FAO Fisheries Technical Paper. No. 489) Rome.

Fedler, A. J., & Ditton, R. B. (2001). Dropping out and dropping in a study of factors for changing recreational fishing participation. *North American Journal of Fisheries Management*, *21*, 283–292.

Finnoff, D., & Tschirhart, J. (2003). Protecting an endangered species while harvesting its prey in a general equilibrium ecosystem model. *Land Economics*, *79*, 160–180.

Flaaten, O. (1988). *The economics of multispecies harvesting—Theory and application to the Barents sea fisheries*. Studies in Contemporary Economics. Springer Verlag.

Flaaten, O., & Stollery, K. (1996). The economic cost of biological predation: Theory and application to the case of the Northeast Atlantic Minke Whale's (Balaenoptera Acutorostrata) consumption of fish. *Environmental and Resource Economics*, *8*, 75–95.

Getz, W. M. (1984). Population dynamics: A per capita resource approach. *Journal of Theoretical Biology*, *180*, 623–643.

Goldsworthy, S. D., Bailleul, F., Nursey-Bray, M., Mackay, A., Oxley, A., Reinhold, S. L., & Shaughnessy, F. D. (2019). Assessment of the Impacts of Seals on the Seafood Industry in South Australia, South Australian Research and Development Institute, Adelaide.

Gordon, D. V. (2015). The endogeneity problem in applied fisheries econometrics: A critical review. *Environmental and Resource Economics*, *61*, 115–125.

Gren, I. M., Svensson, T. H., Elofsson, K., & Engelmann, M. (2018). Economics of Wildlife Management—An overview. *European Journal of Wildlife Research*, *64*, 12–24.

Haarder, S., Kania, P., Galatius, A., & Buchmann, K. (2014). Increased Contracaecum Osculatum infection in Baltic Cod (Gadus Morhua) livers (1982-2012) associated with Increasing Grey Seal (Halichoerus Gryphus) populations. *Journal of Wildlife Diseases*, *50*, 537–543.

Hanley, N., Shogren, J. F., & White, B. (1997). *Environmental economics. Theory and practice*. Red Globe Press.

Hansson, S., Bergström, U., Bonsdorff, E., Härkönen, T., Jepsen, N., Kautsky, L., Lundström, K., Lunneryd, S.-G., Ovegård, M., Salmi, J., Sendek, D., & Vetemaa, M. (2018). Competition for the fish-fish extraction from the Baltic Sea by humans, aquatic mammals and birds. *ICES Journal of Marine Science*, *75*, 999–1008.

HELCOM. (2006). Conservation of Seals in the Baltic Sea Area, HELCOM Recommendation, Helsinki.

HELCOM. (2018). Population Trends and Abundance of Seals, HELCOM Core Indicator Report, Helsinki.

Holma, M., Lindroos, M., & Oinonen, S. (2014). The economics of conflicting interests: Northern Baltic Salmon fishery adaption to gray seal abundance. *Natural Resource Modeling*, *27*, 275–299.

ICES. (2021). Working Group on Marine Mammal Ecology, Copenhagen.

Jansson, T., & Waldo, S. (2022). Managing marine mammals and fisheries: A calibrated programming model for the seal-fishery interaction in Sweden, Environmental and Resource Economics (forthcoming).

Jiang, G., & Lu, Q. (2007). Impulsivestate feedback control of a predator-prey model. *Journal of Computational and Applied Mathematics*, *200*, 193–207.

Johnston, R. J., Rolfe, J., Rosenberger, R. S., & Brouwer, R. (2015). *Benefit transfer of environmental and resource values. A guide for researchers and practitioners*. Springer Verlag.

Jost, C., Arino, O., & Ardil, R. (1999). About deterministic extinction in ratio-dependent Predator-Prey Models. *Bulletin of Mathematical Biology*, *61*, 19–32.

Königson, S., Lunneryd, S. G., Stridh, H., & Sundqvist, F. (2009). Grey seal predation in cod gillnet fisheries in the Central Baltic Sea. *Journal of Northwest Atlantic Fishery Science*, *42*, 41–47.

Lunneryd, S. G., Boström, M. K., & Aspholm, P. E. (2015). Sealworm (Pseudoterranova Decipiens) infection in grey seals (Halichoerus Grypus), cod (Gadus Morhua), and shorthorn sculpin (Myoxocephalus Scorpius) in the Baltic Sea. *Parasitology Research*, *114*, 257–264.

Magera, A., Mills, F. J., Kaschner, K., Christensen, L., & Lotze, H. (2013). Recovery trends in marine mammals populations. *PLOS One*, *8*, 1–13.

Melding til Stortinget. (2020). Helhetlige Forvaltningsplaner for de Norske Havområdene—Barentshavet og Havområdene Utenfor Lofoten, Norskehavet, og Nordsjøen og Skagerrak, Det Kongelige Miljø- og Klimadepartment, Oslo.

Neher, P. A. (1990). *Natural resource economics. Conservation and exploitation*. Cambridge University Press.

Shi, C., Cheri, X., & Wang, Y. (2017). Feedback control effect on the Lotka-Volterra Prey-Predator System with discrete delays. *Advances in Differential Equations*, *373*, 1–13.

Skonhoft, A., Vestergaard, N., & Quaas, M. (2012). Optimal harvest in an age-structured model with different fishing selectivity. *Environmental and Resource Economics*, *51*, 525–544.

Sokolova, M., Buchmann, K., Huwer, B., Kania, P. W., Krumme, U., Galatius, A., Hemmer-Hansen, J., & Behrens, J. W. (2018). Spatial patterns in infection of cod (Gadus Morhua) with the seal-associated liver worm (Contracaecum Osculatum Sensu Stricto) from the Skagerrak to the Central Baltic Sea. *Marine Ecology—Progress Series*, *606*, 105–118.

SwAM. (2018). Havs- och Vattenmyndighetens Föreskrifter om Ændring i Havs- och Vattenmyndighetens Föreskrifter (HVMFS 2012:18) om Vad som Kännetecknar God Miljöstatus samt Miljökvalitetsnormer med Indikatorer för Nordsjön och Östersjön, Havs- och Vattenmyndighetens, Stockholm.

Tahvonen, O. (2008). Harvesting an age-structured population as biomass: Does it work? *Natural Resource Modelling*, *21*, 525–550.

Tahvonen, Q., Quass, M., Schmidt, J., & Voss, R. (2013). Optimal harvesting of an age-structured schooling fishery. *Environmental and Resource Economics*, *54*, 21–39.

Trapper, R. (2006). Wildlife watching and tourism: A study on the benefits and risks of a fast growing tourism activity and its impacts on species. United Nations Environmental Program, Rome.

Vestergaard, N. (1996). Discard behavior, highgrading and regulation: The case of the Greenland shrimp fishery. *Marine Resource Economics*, *11*, 247–266.

Wagersky, P. J. (1978). Lotka-Volterra population models. *Annual Review of Ecology and Systematics*, *9*, 189–218.

Waldo, S., Paulrud, A., & Blomquist, J. (2020). The economic costs of seal presence in Swedish small-scale fisheries. *ICES Journal of Marine Science*, *77*, 815–825.

Westra, J. V., & Boutwell, J. L. (2013). Benefit transfer: A review of methodologies and challenges. *Resources*, *2*, 517–5127.

Xu, R., & Chen, L. S. (2001). Persistence and global stability for a delayed non-autonomous predator-prey system without dominating instantaneous negative feedback. *Journal of Applied Mathematical Analysis*, *262*, 50–61.

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

How to cite this article: Blomquist, J., Jensen, F., Waldo, S., Flaaten, O., & Holma, M. K. (2022). Joint management of marine mammals and a fish species: The case of cod and grey seals in the Nordic-Baltic Sea countries. *Natural Resource Modeling*, e12341. https://doi.org/10.1111/nrm.12341